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Morphogenesis of Interpersonal Synchronization: Revealing How Emotions Shape Joint Action

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ABSTRACT

This dissertation contributes to a vibrant discussion surrounding interpersonal synchronization, the line of research investigating how human beings connect with each other, develop a sense of unity, create meaning, and function as efficient social units. Despite extensive research in the past two decades on joint action, the exact influence of emotions on interpersonal synchronization remains unresolved due to insufficient empirical evidence. To address this lingering uncertainty, the contributions made throughout my Ph.D. program can be categorized into three main areas. First, we conduct a comprehensive critical analysis of the literature on the intersection between emotion and joint action, closely examining theoretical frameworks and emerging findings suggesting their interconnectedness. Second, we juxtapose how synchronization is operationalized across different research domains and analyze the measurement techniques utilized to evaluate synchronization between people. Third, leveraging theoretical and methodological refinements, we make empirical contributions to the realm of interpersonal synchronization by introducing a novel method for naturalistically inducing emotions within the context of joint action and assessing the resulting dynamics in both unstructured and structured experimental contexts. The results highlight the significant impact of emotions on interpersonal synchronization, demonstrating their transformative nature. It is confirmed that emotions possess morphogenic properties that drive and shape the dynamics of interpersonal interactions. Specifically, positive emotions are found to foster interpersonal synchronization, becoming increasingly influential in the unstructured experimental setting. By contrast, negative emotions exhibit a disrupting effect on interpersonal synchronization, with a more pronounced impact in the structured experimental setting. This doctoral dissertation provides a nuanced understanding of how emotions steer human joint action, opening up avenues for further exploration and potential applications in various fields, including social neuroscience, coordination dynamics, and human-computer interaction.

Keywords: *Interpersonal synchronization*, *emotion*, *joint action*, *sensorimotor coordination*, *embodied cognition*, *Kuramoto order parameter*.

RESUME

Cette thèse contribue à la discussion animée sur liens entre synchronisation interpersonnelle et émotion. La synchronisation est un mécanisme biologique fondamental qui permet aux individus de coordonner leurs comportements, d'accorder leurs réponses physiologiques, et d'exprimer collectivement des émotions intenses. Malgré de nombreuses recherches récentes sur l'action conjointe, l'influence précise des émotions sur la synchronisation interpersonnelle reste indéterminée. L'objectif de notre travail doctoral est de mieux comprendre cette influence, dans trois domaines principaux. Premièrement, nous réalisons une analyse critique de la littérature sur l'intersection entre émotion et action conjointe. Deuxièmement, nous analysons comment la synchronisation est opérationnalisée dans différents domaines de recherche connexes, et mettons en avant les techniques variées de mesure utilisées. Troisièmement, nous contribuons empiriquement au domaine de la synchronisation interpersonnelle en introduisant une nouvelle méthode permettant l'induction naturelle des émotions, et en évaluant les dynamiques motrices socio-émotionnelles résultantes dans des contextes expérimentaux non structurés et structurés. Les résultats mettent en évidence l'impact significatif des émotions sur la synchronisation interpersonnelle, témoignant ainsi de leur nature transformative. Nous montrons que les émotions possèdent des propriétés morphogéniques qui orientent et façonnent les dynamiques des interactions interpersonnelles. Plus spécifiquement, montrons que les émotions positives favorisent la synchronisation interpersonnelle, devenant de plus en plus influentes dans le contexte expérimental non structuré. En revanche, les émotions négatives ont un effet perturbateur sur la synchronisation interpersonnelle, avec un impact plus prononcé dans le contexte expérimental structuré. Cette thèse doctorale offre une compréhension nuancée de la façon dont les émotions orientent l'action conjointe humaine, ouvrant des perspectives pour de nouvelles explorations et applications dans divers domaines, notamment les neurosciences sociales, la dynamique de coordination et l'interaction homme-machine.

Mots clés: *Synchronisation interpersonnelle*, *émotion*, *action conjointe*, *coordination sensorimotrice*, *cognition incarnée*, *paramètre d'ordre de Kuramoto*.

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Part I

INTRODUCTION

CHAPTER 1

Introduction

> *"Words are inadequate to describe the emotion aroused by the prolonged movement in unison that drilling involved. A sense of pervasive well-being is what I recall; more specifically, a strange sense of personal enlargement; a sort of swelling out, becoming bigger than life, thanks to participation in a collective ritual."* (McNeill, 1995, p.2).

Participating in a rhythmic collective ritual, as described by historian McNeil, transcends individual experiences and gives rise to powerful and deeply felt emotions. These rituals are what is called joint action (Clark, 1996; Sebanz et al., 2006), when two or more individuals align their actions to achieve a shared goal or perform a common task. Throughout the course of human evolution, joint action has played a significant role in shaping and defining shared experiences and collective endeavors. People united in tribes and showed a remarkable ability to coordinate their strategic positions, signaling, and movements to increase hunting efficiency; musical expressions through harmonious singing and rhythmical drumming became a vehicle for emotional connection, strengthening social bonds; chanting together in agricultural societies fostered a sense of unity and motivation, helping farmers to maintain a constant rhythm of actions, ensuring the efficient execution of tasks to increase agricultural productivity. Participating in synchronized activities fosters a deeper level of coordination and unity within the group, thereby increasing the likelihood of success in other collaborative activities (von Zimmermann and Richardson, 2016). The realm of joint action has captured the curiosity of researchers, presenting a captivating avenue to unravel the complexities of the human mind through social interactions. Emotions, being integral to human interactions, add a layer of depth and richness to the understanding of joint action and serve as the focal point of this dissertation. It is by delving into the complex realm of joint action that we analyze the underlying mechanisms that shape and define shared experiences, and pushing the boundaries of current knowledge about the interplay between emotion and interpersonal synchronization is the general goal of my doctoral work.

1.1 Exploring the subjective experience: unveiling the interplay between joint action and emotion in the case of the Viking Thunder Clap

The interconnectedness between emotions and joint action is evident in numerous contemporary contexts, such as music, arts, and sports, showcasing the profound influence of emotional states on collective behaviors and interactions. To paint a vivid picture, imagine you are immersed among the thousands of passionate fans gathered from afar on Arnarhóll, a prominent hill overlooking Reykjavík, Iceland's vibrant capital city. You are part of the crowd that came together to fervently cheer on the national football team during the exhilarating UEFA Euro 2016 tournament held in France. Gathered around a colossal video screen, the passionate crowd fixes their gaze on the live broadcast. Amidst the electric atmosphere that fills the air, a deep sense of collective unity and camaraderie envelops the crowd. As the moment approaches for them to engage in the iconic Viking Thunder Clap[1], the crowd falls silent, a sense of anticipation and excitement builds in the air[2].

With two rhythmic beats of the drum, a loud clap echoes through the hill as thousands of people come together, producing a powerful and synchronized sound, accompanied by a resounding "huh" chant. The sound reverberates, intertwining with the cheers of thousands of voices coming together as one, a surge of adrenaline courses through the veins. In this moment, individual identities dissolve, giving way to a powerful sense of belonging to a greater whole. A hushed silence descends upon the surroundings. Once again, the air reverberates with the two rhythmic beats of the drum, the crowd bursts into the electrifying Viking Thunder Clap, punctuated by the powerful and unifying "huh" chant. The sound complements the rhythmic clapping that permeates the body and helps to further solidify the sense of togetherness. Silence reclaims its dominion over the hill, hushing any lingering sounds. As the cycle repeats, the intervals between the rhythmic clapping shorten, fueling a crescendo of collective shouts and roars that reverberate through the crowd, heightening the immersive and exhilarating nature of the experience. Adrenaline surges with every clap, amplifying passion and enthusiasm. A surge of euphoria washes over in a moment of pure invigoration, a testament to the power of unity and shared passion. The Viking Thunder Clap has gained international attention and has been adopted by fans of various sports teams around the world in a powerful display of unity, unwavering support, and a formidable presence that instills fear in the opposing teams.

[1] https://www.youtube.com/watch?v=0JdpRWG3IJ0
[2] https://www.youtube.com/watch?v=q1qGRUn2Jdo

1.2 The social consequences of the interconnectedness between joint actions and emotion

The example of the Viking Thunder Clap serves as an illustration of the profound social implications that arise from engaging in rhythmic interactions with others. Interpersonal synchrony is a natural biological phenomenon that enables individuals to effortlessly align their emotions and behavioral patterns, leading to the development of socio-emotional outcomes Burgoon et al. (1995). It is crucial to note that synchrony, in this context, does not represent the end results but rather act as a facilitating mechanism through which these outcomes are achieved (Strang et al., 2013). Given that synchrony is a pervasive feature of human social interactions, there exists a wide range of manifestations for these outcomes. These include enhanced predictability between interaction partners, which facilitates communication and subsequent joint action, as well as the formation of affective bonds among individuals in small and large groups (Hoehl et al., 2021). By recognizing these mechanisms, we gain a deeper understanding of the social implications that emerge in diverse contexts, encompassing both small groups and larger scales. Moreover, this recognition significantly contributes to our overall comprehension of social dynamics at cultural, societal, and national levels.

1.3 The power of propaganda: unveiling the role of emotions

The profound significance and impact of emotions on society prompt an insightful discussion on their influential role in shaping both individual experiences and collective dynamics. The pivotal role of emotions in the realm of propaganda and social opinion engineering highlights their instrumental power in shaping perceptions, constructing attitudes, manipulating narratives, and influencing collective beliefs and behaviors (Bernays, 1928). Given that the human brain is inherently predisposed to create an ”Us/Them” dichotomy (Sapolsky, 2017), i.e., distinguishing between individuals of their own group and those outside it, propaganda capitalizes on this natural tendency.

The role of emotions in shaping and developing human culture is of great importance, as they have profound impact on the formation, maintenance, and transformation of both cultural norms and national identity (Kashima et al., 2020). Emotions, which have evolved from individual experiences, become powerful forces driving cultural and societal dynamics (Rozin et al., 2009). Through targeted messages that appeal to cultural norms and national identity, propaganda skillfully exploits public sentiment to amplify group differences. By strategically leveraging emotions such as fear, anger, pride, and disgust, these propaganda techniques manipulate and shape public opinion, further deepening the divide between ”Us” and ”Them”. Propaganda operates by fostering a sense of superiority and unity within the ”Us” group, while concurrently dehu-

manizing and vilifying the "Them" group [3]. This perpetuates a divisive narrative that effectively widens the gap between ingroups and outgroups, exacerbating societal divisions and undermining social cohesion. Despite the significant research interest in the field of emotion and joint action, the role of emotion in shaping and influencing collective behavior and coordination remains largely uncharted territory, warranting further investigation and exploration.

1.4 Research challenges

Some of the examples presented above substantiate the necessity of exploring the interconnectedness between emotion and joint action. Despite the presented finding the fields of emotion and joint action remain separate strands of research. Moreover, studying groups is not the same as studying dyads, let alone individuals. Recognizing the importance of emotions and integrating them into scientific investigations can lead to more comprehensive and meaningful insights into the complexities of the human experience.

1.5 Our research focus

In our exploration, it is important to differentiate between the concepts of coordination and synchronization. Coordination is a broad term that encompasses a wide range of adjustments in behavior, including actions like mimicry or mirroring. On the other hand, our primary focus lies in the phenomenon of synchronization, which specifically refers to the adjustment of rhythms of the phases (Jirsa and Kelso, 2011). This adjustment occurs due to weak coupling between oscillators, where individuals or systems entrain their rhythms to achieve temporal alignment (Pikovsky et al., 2001).

In this dissertation, our primary focus is on understanding and investigating i) theoretically, ii) methodologically and iii) experimentally the interplay between emotions and interpersonal synchronization processes. By delving into the emotional processes, we aim to unravel the intricate mechanisms involved in achieving harmonious rhythmical coordination among individuals.

By focusing on these three aspects, we aim to contribute to a deeper understanding of interpersonal synchronization processes and shed light on the complex interplay between emotion and interaction dynamics. Our research endeavors to provide valuable insights into the mechanisms underlying rhythmic behavior, how emotional states contribute to the coordination, overall quality of joint actions, and enhance our knowledge of social coordination in various contexts.

[3] https://www.youtube.com/watch?v=yk5RDy6xFJQ

1.6 Our contributions

The scientific contributions of this thesis encompass a range of significant findings and advancements of knowledge in the fields of social neuroscience, nonlinear dynamics, and affective computing. The following summary highlights some of the key contributions that I have made throughout my PhD program:

- Thorough assessment of the **current body of knowledge** about **joint action research** revealed a critical area of investigation of the delicate interplay between emotions and joint action that has not yet received the necessary attention.
- Elucidation of the **methodological framework** that reflects **interpersonal synchronization as a dynamical process** to ensure consistency in the operationalization of the phenomenon in social science research, thereby enhancing reproducibility.
- Critical evaluation of **existing methodologies** and standard practices **used for emotion induction** led to the development of a novel emotion induction method that offers a balanced exchange between ecological validity and experimental control, both at a high standard.
- Conducting a series of **original empirical studies** that testify to the influence of emotions on rhythmic joint action, contributing to the advancement of the existing knowledge base.

1.7 Thesis structure

This dissertation consists of five parts: 1) Introduction 2) Related work, 3) Research themes and questions, 4) Personal contributions, and 5) General discussion, implications, and conclusion. The second part of the manuscript situates the research within the broader theoretical foundations, and research context for my dissertation.

The third part of the manuscript exposes the research themes to respond to the identified research problematics. In Chapter 5, each of the themes contains a list of specific research questions that were addressed in the published peer-reviewed articles.

In the fourth part, I demonstrate my individual contributions to each research theme through original publications. The section is organized into 4 chapters. Chapter 6 explores theoretically the subtle interaction between emotions and joint action. Chapter 7 advocates for reassessing the methodology of the evaluation of interpersonal synchronization and showcases the pressing need for establishing operational definitions. Chapter 8 presents the first experimental study of the effect of emotion on interpersonal synchronization in an unstructured context. Chapter 9 describes the second experi-

mental study of the effect of emotion on interpersonal synchronization in a structured context.

The last, fifth part of the manuscript constitutes the general discussion and identifies both theoretical and applied perspectives concerning the evaluation of emotions. In Chapter 10, I summarize the results, identify limitations, discuss perspectives and implications, and present conclusions.

Part II

RELATED WORK

CHAPTER 2

Exploring the Science of Interpersonal Synchronization: Synergy with Emotions

Within this chapter, our aim is to introduce and explore the theory of interpersonal synchronization. Throughout the entirety of the chapter, we strive to provide insights into the complex and nuanced role of emotional values in this process. Understanding how emotions both influence and are influenced by joint activities is of paramount importance. While we emphasize the positive aspects of interpersonal synchronization, it is also essential to acknowledge and discuss potential negative outcomes that can arise from it.

2.1 The Economic Burden of Affective Disorders in Modern Societies

Affective disorders, such as depression and anxiety disorders, pose a significant economic burden for modern societies. These burdens manifest in various ways, including economic costs and social impact, such as reduced increased healthcare utilization, provision of care and treatment cost. According to a study conducted by Wittchen et al. (2011), the number of people affected by anxiety disorder in Europe saw a significant increase in recent decades. In 2005, there were approximately 82 million individuals affected by mental disorders. However, by 2011, this number had risen to 165 million, which accounts for 38.2% of the European population suffering from mental disorders. Out of this portion of the population, around 14% or 23.1 million people were diagnosed with anxiety disorder, and 6.9% or 11.4 million people suffered from major depression.

Affective disorders impair the efficiency of persons in the workplace and therefore reduce productivity. Anxiety disorders, a prominent mental health condition, serve as a major contributor to disability. Surprisingly, these disorders often go unnoticed and untreated by healthcare systems, even in economically advanced nations. This lack of detection and treatment can result in individuals experiencing persistent feelings of fear, avoidance of perceived threats, and consequent difficulty in leaving their homes (Craske et al., 2017).

Given the economic situation in many countries, it is important to conduct a thorough investigation into the necessary steps that need to be taken, while also carefully estimating the associated risks and benefits. Chisholm et al. (2016) conducted a study that involved a global return on investment analysis on 36 large countries, collectively representing 80% of the world's population. The analysis highlighted the substantial investment required to enhance the global treatment of affective disorders between 2016 and 2030, amounting to approximately US$147 billion. This figure may seem staggering, but the study also projected significant returns on this investment, with an estimated net value of $310 billion and an additional 43 million of healthy life-years over the same period. These data demonstrate the significance of affective well-being in society and provide a strong motivation for further research aimed at understanding the affective and emotional processes underlying human interactions.

2.2 The Diminished Emotional Well-Being in the Absence of Joint Action

The outbreak of the recent COVID-19 pandemic led most governments to impose mobility restrictions on the population and even constrained many nations with severe confinement. The measures taken have led to the deprivation of many people of the possibility of social interactions, which demonstrated the high cost of social distancing for various demographic groups due to a decline in emotional and general well-being (Pedrosa et al., 2020). The multifaceted consequences of the pandemic have hit youth particularly hard, with heightened anxiety and depression due to disruptions in the educational process and a lack of social contacts when they are essential for healthy emotional development (Nearchou et al., 2020). Despite the increased knowledge and gathered data, accurately estimating the immediate and long-term mental health impacts of the pandemic on children remains a formidable task (Jones et al., 2023). It is through the unfortunate loss of social interaction caused by the COVID-19 pandemic that many people have come to appreciate the profound impact of emotions on our social lives, that we yearn for the warmth of a meaningful connection, the shared laughter, and the emotional resonance resulting from sensorimotor interaction with other people.

2.3 Joint Action is driven by Interpersonal Synchronization

Interpersonal synchronization serves as the fundamental driving force behind joint action, enabling seamless coordination among individuals (Sebanz et al., 2006). It is the primary process responsible for the adaptive changes that occur during interactions (Burgoon et al., 1995). Various ways exist through which individuals adapt and converge to one another, including similar behaviors, bodily postures, speech, and gestures.

However, rhythm is emphasized as a crucial factor in understanding synchronization (Dunbar et al., 2022). In interaction, human bodies act like a harmonious orchestra, with different rhythms converging and intertwining to create a synchronized symphony. For example, when people are together and singing, their respiratory and cardiac rhythms synchronize (Müller and Lindenberger, 2011). Athletes rowing together experience an increase in endorphin levels due to behavioral synchrony (Cohen et al., 2010). During the first half-year of parenting, the oxytocin levels of parents tend to converge (Gordon et al., 2010). Females living together often synchronize their menstrual cycles (McClintock, 1971). Even when jointly watching emotional video clips, brain synchronization can occur (Hasson et al., 2004). Through participation in collective rituals, emotional resonance is enhanced (Collins, 2004). This resonance involves the synchronization of emotional arousal and excitement intensities (Páez et al., 2015; Pizarro et al., 2022; Xygalatas et al., 2011). These examples vividly illustrate the intrinsic nature of timekeeping, which serves as a biological clock of multi-cellular organisms on Earth (Bargiello et al., 1984). But as physicist Strogatz aptly put it, ”we might not have a clock; we might *be* a clock” (Strogatz, 2003, p.87).

2.4 The Emergence of the Science of Inanimate Synchronization

The phenomenon of synchronization was discovered incidentally (Pikovsky et al., 2001). As Strogatz (2003) describes, in the late 17th century, the Dutch mathematician Christian Huygens sought to resolve a remarkable technological challenge of his era. The challenge held immense significance during the age of exploration, trade, and territorial expansion: determining longitude at sea. In order to evade pirates and navigate safely without deviating hundreds of kilometers off course, the maritime authorities of the European continent were actively searching for a solution to accurately determine longitude at sea. Despite the efforts of brilliant minds like Galileo Galilei and Isaac Newton, the problem remained unresolved for four centuries. The core of the problem was that latitude could be measured easily by observing the day’s length or the sun’s height, representing a ship’s distance from the equator. However, longitude, which denotes a ship’s east-west position on the globe, lacked a natural reference point in the environment and was arbitrarily defined at that time.

A century prior to this, the solution to the challenge had actually been proposed by another Dutch scientist named Gemma Frisius. However, due to the lack of adequate technology, his proposal remained unverified. Frisius suggested that latitude could be accurately determined by precise timekeeping. The concept was remarkable in its simplicity and ingenuity. In essence, by daily comparing the time of departure port with the local noon time, the navigator could calculate the ship’s longitude. Since the Earth com-

pletes a full rotation of 360 degrees in 24 hours, each hour of time difference between the “home time” and the local time corresponds to 15 degrees of longitude, which approximately equals 1000 miles at the equator. Unfortunately, the most advanced clocks of that era, even without disturbances like humidity, pressure, and temperature which are commonly encountered at sea, would still lead to a deviation of 15 minutes per day. Consequently, Frisius’s proposed method could not be validated.

To remedy the problem of inaccurate clocks, Huygens invented pendulum clocks in the mid-17th century that could have deviations of only a couple of seconds daily. With this technological advancement, he embarked on a sea trial to Cape Verde Islands with two pendulum clocks for security reasons, if one needed cleaning or if stopped. This approach allowed Huygens to confirm Frisius’ reasoning by correctly identifying the longitude throughout the travel. However, he was stuck and mesmerized by one fact that he noticed. He remarked that when the two clocks were hung next to each other with the same rhythm and even if he changes manually their rhythms, they unequivocally return to harmony within a short period of time. However, as the clocks were further separated from each other, their rhythms began to diverge. Through further experimentation (Fig. 2.1), Huygens deduced that the synchronization between pendulums, which he referred to as sympathy, emerged between the clocks due to the vibrations transmitted through their shared support (Strogatz, 2003). This anecdote of the synchronization discovery holds immense significance as it highlights the initial breakthrough in synchronization research: the acknowledgment of the fundamental role played by coupling.

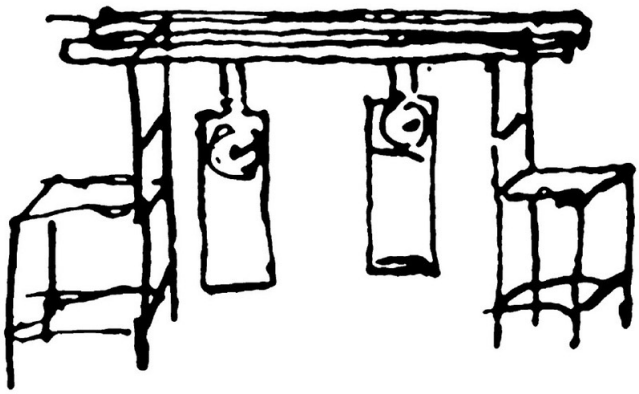


Fig. 2.1 Huygens’ drawing of sympathy between two clocks. Source: https://www.networkpages.nl/synchronization/.

2.5 Demystifying human interpersonal synchronization: Exploring the causes

Several authors, such as Rennung and Göritz (2016) and Novotny (2021), have made efforts to explore the underlying causes that contribute to the emergence of the interpersonal synchronization phenomenon. Interestingly, both authors presented three reasons that are somewhat overlapping yet complementary. Hence, we will now proceed to discuss the three reasons sequentially.

The first reason resolves around the socio-emotional process that dissolves individuality within a group, leading to a merging with others (Paladino et al., 2010). The citation with which we began this dissertation served the purpose of illustrating this transcendent and emotional experience, resulting from *"a sense of personal enlargement; a sort of swelling out, becoming bigger than life, thanks to participation in a collective ritual"* (McNeill, 1995, p.2). Moreover, the nature of emotions, as observed through emotional contagion (Hatfield et al., 1994), contributes to the synchronized intensities of emotional arousal, as in the Viking Thunder Clap. These shared emotions give rise to the phenomenon of collective effervescence (Durkheim and Fields, 1995) which holds beneficial and adaptive effects for the group (Pizarro et al., 2022).

The second reason arises as a direct consequence of the first one and is represented by the evolutionary significance of becoming a functional social unit. For instance, the synchronous singing of males in large groups serves as an attraction for potential mates of migrating females due to the loud acoustical signal it generates. This signal indicates the presence of large groups of individuals, which in turn signifies abundant resources and high levels of cooperation (Rennung and Göritz, 2016). Moreover, being in synchrony with others facilitates cohesion (Launay et al., 2016), rapport (Miles et al., 2009), affiliation (Hove and Risen, 2009), and cooperation (Valdesolo et al., 2010). Synchronization is believed to develop a foundation for the emergence of functional units for performing the task (Nowak et al., 2017). One example is the integration of synchronous military drills into the army to develop stronger military units (McNeill, 1995).

The third reason pertains to the physical properties that result from being coupled. This process occurs automatically and is tied to the brain optimization principle (Koban et al., 2019). when the number of predictive errors is reduced, computational processes become more efficient, resulting in decreased neural energy consumption. This reduction in prediction errors triggers the release of dopamine, which serves as a reward (Schultz, 2006). Importantly, dopamine has also been found to reinforce the connection between motor planning and interpersonal synchronization (Gvirts Probolovski

and Dahan, 2021). Additionally, Müller (2022) proposed a *Hyper-Brain Cell Assembly Hypothesis*, which suggests that coupled physiological systems give rise to cell assemblies through synchronized ignition of neural cells and nodes within and between brains Remarkably, a similar principle was also observed in linguistic dyadic conversation, where Garrod and Pickering (2004) demonstrated the use of converging linguistic representations effectively reduces computational demands. Collectively, these findings demonstrate that synchrony is not merely a consequence of social interaction; rather, it functions as the underlying mechanism driving social interaction and the resulting socio-emotional outcomes (e.g., Strang et al., 2013).

2.6 Exploring the human developmental significance of interpersonal synchronization

At its core, interpersonal synchronization is vital for human development. Indeed, as early as the 20th week of fetal development in the womb, synchrony between fetal movements and maternal skin conductance and heart rate is detected (DiPietro et al., 2006). In early human development, moving in synchrony with an infant increases his propensity for prosocial behavior (Cirelli et al., 2014). In addition, synchronization levels in the first year of life predict empathetic abilities during adolescence (Feldman, 2007b). First experiences of behavioral and physiological synchrony in an infant's first social dyads provide the backbone for the development of emotional skills, e.g., emotion labeling and regulation (Atzil and Gendron, 2017). Furthermore, the mirroring of toddlers' affective states by parents is a cornerstone for infants' empathy, creativity development, and symbol formation. It is important to note that the affective attunement patterns of the infant's first social dyad are parent-specific (Feldman, 2007a). Difficulties in establishing rhythmic coordination in child-mother dyads were revealed when mothers suffer from affective pathological conditions, such as clinical depression and anxiety (Feldman, 2007c). Toddlers, as early as around 15 months old, have been found to make inferences about affiliation by observing movement synchrony (Fawcett and Tunçgenç, 2017). The importance of synchronization persists throughout adulthood.

2.7 Exploring the positive outcomes of interpersonal synchronization

Engaging in rhythmical interactions with other people has important social implications. In recent years, several comprehensive literature review articles have drawn attention to and concisely summarized the diverse spectrum of social outcomes that result from participating in rhythmical joint action. For example, Rennung and Göritz (2016) performed a meta-analysis to consolidate and reconcile diverse findings from individual studies that frequently involved homogenous participant groups. Their specific focus

revolved around exploring the influence of motor-sensory interpersonal synchrony on prosociality in 60 independent experiments, resulting in a moderate effect in both prosocial attitudes and behaviors. In another review including 128 effect sizes from 50 studies, Vicaria and Dickens (2016) supported the findings of enhanced prosocial behavior with an effect size falling just below a moderate threshold. Additionally, they found that individual outcomes included reduced anxiety and interdependent self-construals (i.e., self-identification through relationships, not personal attributes) with both significant but weak effect sizes. Furthermore, Mogan et al. (2017) analyzed 42 independent studies and found a medium effect size effect on prosocial behavior and also positive but small effect on perceived social bonding, social cognition and affect. By contrast, Cross et al. (2019) conducted a review of 56 experimental publications and suggested that social bonding is not an inevitable consequence of interpersonal synchronization. They argued that the multifaceted outcomes stemming from interpersonal synchronization, including shared emotions and actions that foster group formation, can bypass social bonding. To provide an accurate summary of the social effects of interpersonal synchronization, it is essential to adopt a pro-group perspective that extends beyond the scope of solely examining prosocial outcomes. Finally, the synchronization of individuals' movements and actions with others generates a sense of rapport, affection for others, and connectedness within the group (Hoehl et al., 2021). While the research presented so far supports the notion that interpersonal synchronization plays a crucial role in social interaction and positive outcomes, it is important to acknowledge that not every instance of synchronization may necessarily be beneficial.

2.8 Exploring the side effects of interpersonal synchronization

When examining synchronization from a qualitative perspective, it becomes evident that the phenomenon can yield some negative consequences. For instance, in terms of brain activity, the occurrence of seizures and epilepsy can be attributed to an abnormal and excessive synchronous firing of a large population of brain cells disrupting the normal electrical patterns and functioning of the brain that are manifesting through seizures and uncontrolled rhythmic convulsions (Fisher et al., 2005). However, it is important to recognize that there are additional drawbacks that arise from interpersonal synchronization such as poor team performance, weakened self-identity values or physiological synchrony in emotional distress. These potential disadvantages should not be overlooked and we address them in turn in this section.

2.8.1 Decreased team performance

A growing body of empirical evidence suggests that enhanced interpersonal synchronization is not always advantageous for team performance. Consequently, a thorough

analysis of the experimental context from which these counterintuitive findings were derived is imperative for further understanding of the effects of interpersonal synchronization. Within this subsection, we will analyze three recent experimental studies.

The first study (Abney et al., 2015) involved the participation of 25 dyads consisting of adults who were motivated by the prospect of earning extra course credits. The joint action task assigned to them was to construct towers within a 15-minute timeframe, utilizing one box of uncooked spaghetti and one box of marshmallows. Participants were seated adjacent to each other and given specific roles: one individual exclusively manipulated the uncooked spaghetti and the other solely handled the marshmallows. The researchers employed cross-recurrence analysis of pixel changes between frames to quantify the synchronization of overall movement for each participant. Notably, the findings demonstrated that lower movement synchrony was associated with higher performance in building taller towers strength (Abney et al., 2015).

In the second study (Wallot et al., 2016), a total of 37 adult dyads participated, with participants being compensated approximately 47 EUR for their involvement in the experiment. The objective was for the dyads to cooperate in building a visually appealing car model by utilizing the maximum number of car pieces within four 10-minute building sessions. The task was conducted under different experimental conditions that imposed restrictions on their movements and the division of labor. These conditions included: ”egalitarian cooperation” (no specific instructions regarding labor division), ”hierarchical cooperation” (one participant assigned a leadership role while the other could only provide assistance), and ”turn-taking” condition (participants alternated in building the car model). To capture synchrony, wrist accelerations were analyzed using multidimensional recurrence quantification analysis. Interestingly, interpersonal synchrony and the number of car pieces used had divergent effects on the success of building car models within different experimental conditions. Synchrony was highest in the ”turn-taking” condition, followed by the ”hierarchical cooperation” condition, and lowest in the ”egalitarian cooperation” condition. However, the opposite effect was observed for the number of pieces used, which ultimately resulted in lower-quality car models (Wallot et al., 2016).

In the third study (Vink et al., 2017), a total of 183 school child dyads voluntarily participated in the experiment. The task involved using tangram puzzles, where the children were provided with puzzle pieces and required to correctly place them on preprinted figures within a 10-minute timeframe. The puzzle pieces needed to correspond in size and be rotated in order to fit the figures. During the cooperative task (the second part of the experiment), the children stood side by side on two Nintendo Wii Balance Boards placed approximately 10 cm apart. This setup enabled the measurement of postural

sway synchronization. Cross-recurrence quantification analysis was employed to evaluate the degree of synchronization in their postural sway. Notably, the results indicated that postural interpersonal synchrony was linked to decreased team performance compared to individual scores. Therefore, the authors concluded that loosely coupled systems demonstrated superior performance compared to synchronized systems (Vink et al., 2017).

In diverse experimental settings, involving a significant number of participants, varying incentives, populations, and notably different tasks, the findings consistently indicated that an increase in interpersonal synchrony led to a decline in group performance. However, we contend that these results should not be viewed as counterintuitive. Instead, it is crucial to acknowledge that synchronous movements are not an inherent feature of all successful forms of interaction. Achieving successful team outcomes sometimes requires adopting different strategies, such as task division into complementary subtasks or working in an antagonistic manner, which can result in more improved team performance and, consequently, a more successful group outcome (Jarrassé et al., 2012). Likewise, in the domain of linguistic dyad research, participants who exhibit unselective alignment of their linguistic behavior experience a decline in collective advantages, hindering their ability to optimize coordinative language use in joint-decision dialogue tasks (Fusaroli et al., 2012). Therefore, the assessment of the negative effects of behavioral synchrony on team performance remains inconclusive, suggesting that in certain cases, task constraints may necessitate the adoption of alternative cooperative strategies instead of synchronous movements.

2.8.2 The weakened self-identity values

Recent empirical studies shed light on the important role of rhythmic interactions on self-identity values, particularly in either deepening the division or bridging the gap between ”Us” and ”Them”. Engaging in interpersonal synchronization with an outgroup promotes cooperation to a greater extent than with an ingroup (Cross et al., 2021), while simultaneously reducing prejudice and stereotypes towards those categorized as ”Them” (Atherton et al., 2019; Tunçgenç and Cohen, 2016). However, it is important to note that synchronous interactions can also have undesirable consequences on the division between ”Us” and ”Them”. For instance, engaging in synchronized movements with an ingroup can lead to a reduction in trust toward outgroup members (Tamborini et al., 2018) and unreflectively embracing a morally discordant group ideology, including outgroup aggression (Cross et al., 2019) or conform to nonsensical choices (Dong et al., 2015). Moreover, synchrony with an authoritative figure can lead to destructive obedience, as measured by the number of bugs inserted into the coffee grinder (no animals were actually harmed). Participants assigned to the condition involving move-

ment synchrony with an authoritative figure displayed a greater willingness to obey the instructions to put as many bugs as possible into the coffee grinder (Wiltermuth, 2012). These findings challenge the assumptions about the stability and resilience of one's self-identity, suggesting that synchronous experiences have the potential to significantly influence and even undermine our core sense of self.

2.8.3 Physiological synchrony as a proxy for negative emotions

When individuals experience emotional distress, their physiological responses may align with each other. Research has shown that synchronization in certain physiological measures occurs after inducing negative emotions, such as the synchronization of zygomaticus EMG (Mønster et al., 2016). Additionally, cardiac synchrony has been found to be negatively correlated with task performance in a cooperative video game (Strang et al., 2011). Levenson and Gottman (1983) conducted a study involving distressed and non-distressed marital couples discussing a highly conflicted topic to examine the exchange and reciprocity of negative affect and its impact on marital satisfaction. The hypothesis was that higher levels of negative affect would lead to stronger "physiological linkage," resulting in lower marital satisfaction. The findings revealed that 60% of the variation in marital satisfaction during negative affect exchanges could be explained by this "physiological linkage" alone. Furthermore, respiratory sinus arrhythmia linkage in marital couples was found to be indicative of social relationship quality, particularly related to reports of marital conflict (Gates et al., 2015). Palumbo et al. (2017) propose that interpersonal synchronization related to negative emotions is better detectable through physiological measures of the sympathetic nervous system, while measures of the parasympathetic nervous system are better suited for assessing positive emotions. The synchronization of physiological activity implies the existence of underlying mechanisms such as emotional contagion or empathetic resonance. These mechanisms suggest that negative emotions play a role in transmitting distress signals and potentially strengthening the connection between individuals.

2.9 Exploring the mediation of interpersonal synchronization

There is a large number of potential moderators of synchronous interaction, such as timing (e.g., Russell et al., 1980), individual differences (e.g., Miles et al., 2011; Nessler and Gilliland, 2009; Słowiński et al., 2016), propensity for pro-sociality (Lumsden et al., 2012) among others. Instead, here we discuss the basis for the mediation of interpersonal attunement such as establishing coupling through physical presence, the affective background with the individual, the perceptual interaction and the affective powers of touch.

2.9.1 Mere presence

Establishing interpersonal coupling relies on the presence of individuals in a shared physical space. Empirical evidence suggests that the mere act of being together, without engaging in conversation or making gross movements, can lead to synchronization of electrodermal and heart rate activity (Golland et al., 2015). This raises an important question about whether socio-emotional effects of synchronization can occur in the presence of individuals with whom strong affective ties have previously been developed or any individual, including complete strangers (Helm et al., 2012).

The socio-motor synchronous interaction among strangers can result in positive outcomes such as increased closeness (Tarr et al., 2016), pain tolerance (Sullivan and Rickers, 2013), and neural phase synchronization in the theta band, which is implicated in emotional processing (Yun et al., 2012). However, it appears that mere presence with any individual is generally insufficient. People are inclined to coordinate movements with acquittances rather than strangers (Latif et al., 2014). And the strength of affective ties between individuals moderates this effect. For instance, in a Spanish fire-walking ritual, the relatives of the fire-walkers showed stronger cardiac synchrony with the fire-walkers compared to strangers (Konvalinka et al., 2011). Thus, the existence of social relationships and shared emotional connections between individuals seem to play a significant role in promoting successful synchronization and its associated socio-emotional effects.

2.9.2 Perceptual interaction

Perceptual interaction involves the exchange and interpretation of sensory information, including facial expressions, body language, and gaze direction. These cues enable individuals to detect and understand the emotional states of others, laying the foundation for interpersonal coupling. According to the findings of Tomashin et al. (2022), it has been observed that during the baseline measure before the interaction, the cardiac activity does not exhibit synchronization and remains at chance levels. This suggests that it is through the actual interaction that coupling emerges.

In this context, it becomes evident that eye contact plays a crucial role in fostering interpersonal coupling that improves speech comprehension and communication (Richardson and Dale, 2005) and increases behavioral mimicry Wang et al. (2011). Experimental manipulations of the visual focus reveal that it is by paying attention to the movement of the other person that interpersonal coupling arises Richardson et al. (2005). Interestingly, even when participants are explicitly instructed not to synchronize, they still exhibit movement oscillation synchronization, highlighting the innate tendency for coupling (Issartel et al., 2007). Furthermore, the topological settings of interaction patterns

affect synchronization, emphasizing the impact of different visual contexts on coupling (Alderisio et al., 2017; Bardy et al., 2020). It is through the exchange of sensory information that coupling occurs (Battich et al., 2020), akin to the synchronization of Huygens pendulum clocks. As individuals engage in perceptual interaction and interpersonal coupling develops, a fascinating phenomenon emerges: the ability to "tick collectively" (Hasson et al., 2012, 2004).

2.9.3 Touch and its intriguing analgesic effect

Touch is more significant than a mere sensorimotor stimulation of the skin. When individuals sing together, touch enhances respiratory synchronization, although there is a comparable inclination for convergence in heart rate variability, its significance was not observed (Lange et al., 2022). However, evidence of increased interpersonal cardiac synchrony resulting from touch was observed by measuring the electrocardiogram method (Goldstein et al., 2017). In romantic couples, the utilization of touch to express affection leads to the occurrence of electrodermal synchrony across various conditions of emotional intensity and valence (Chatel-Goldman et al., 2014). When individuals engage in the embodied simulation of synchronous visuotactile stimulation, where they watch a video of someone else's right cheek being stroked with a cotton bud while receiving synchronous strokes on their own face, it significantly enhances the subsequent recognition of fear (Maister et al., 2013). Additionally, the degree of embodiment experienced can be influenced by depersonalization experiences, which involve feelings of being detached from their own body and are measured using the Cambridge Depersonalization Scale. Those with low depersonalization scores perceive the touch, especially self-stroking, as more pleasant, while individuals with high depersonalization scores perceive it as more negative (Ciaunica et al., 2021). From these findings, we can infer that touch strengthens interpersonal coupling and often has emotional outcomes.

Emerging research suggests that pain and emotion, often viewed as distinct constructs, may actually have a closer relationship than previously believed. This is primarily because they both rely on the utilization of shared neural pathways that are essential for human survival (Gilam et al., 2020). Goldstein et al. (2018, 2020) conducted a series of studies examining the coupling between touch and pain. In one study, they investigated the electrocardiogram and respiration of heterosexual couples who had been together for at least one year. The participants were exposed to three experimental conditions: sitting together not touching, sitting together holding hands, and sitting in separate rooms. In each condition, the woman experienced mild heat-induced pain. The results revealed that touch enhanced the synchronization of heart rate and respiration (Goldstein et al., 2017). In the second study, touch as a female analgesic was also confirmed in brain-to-brain coupling yielding the lowest scores in the condition no touch no pain, but once

the physical coupling was created by holding hands, the brain synchronization emerged and was even further strengthened in the touch-pain condition (Goldstein et al., 2018). In a subsequent study that did not involve romantic partners, the movement synchrony between clinician and patient in simulated clinical interaction was found to decrease the subjective perception of experienced pain (Goldstein et al., 2020). It is noteworthy that motor synchronization has been found to increase the pain threshold in both in-phase (Tarr et al., 2016) and anti-phase (Sullivan and Blacker, 2017) interactions. Taken together, these studies shed light on the augmenting effect of touch on interpersonal coupling processes across various modalities, demonstrating the analgesic effects and highlighting the relevance of touch in clinical and pain management contexts.

In the course of our research up to this point, we have discovered a strong connection between interpersonal synchronization and emotional processes. These findings highlight the need for further investigation into the nature of how these emotional processes shape synchronized actions. It raises important questions about how emotions manifest in relation to interpersonal synchronization and prompts exploration into the underlying mechanisms of these emotions. But first, to lay the groundwork for a deeper exploration of the topic, it is essential to begin by examining the fundamental nature of emotions. Specifically, what precisely do we mean when we refer to emotions?

Summary of Chapter 2

- Synchronization is a pervasive and fundamental tendency towards temporal order present in studied various domains.
- Interpersonal synchronization is an innate biological inclination in humans, serving as a fundamental tendency for individuals to attune and align with one another. This phenomenon carries a multitude of socio-emotional benefits, fostering connection, cooperation, and positive social outcomes.
- Coupling plays a pivotal role in the process of synchronization.
- Merely being physically present is insufficient to initiate the process of synchronization.
- Perceptual interaction forms the basis for establishing coupling between individuals.
- Emotions seem to have a role in modulating coupling between individuals, although the precise impact remains uncertain.

CHAPTER 3

Theory of emotions and their role on human behavior

The focus of this chapter revolves around the essential characteristics of emotions and providing insights into their behavioral expressions. The intrinsic ties between emotion and movement are evident, as they are not only reflected in the word ”emotion” containing the word ”motion”, but also in its etymology derived from the Latin term *”emovere”*, which translates to ”to move”. Accordingly, emotions can be understood as serving the purpose of instigating change in an agent's environment through behavior. A notable illustration of this is the fight or flight response, which exemplifies how individuals when feeling anger, prepare themselves to confront a threat, while in the case of fear, they prepare to escape from the perceived danger. In this chapter, we will specifically focus on the challenges encountered by theories of emotion and explore emerging evidence highlighting the intricate effect of emotions on the motor control system.

3.1 Exploring the challenges in studying emotions

There exist numerous obstacles in the field of emotion research. More than 40 years ago, over 90 different definitions of emotion were identified (Kleinginna and Kleinginna, 1981), and to this day, there remains no widely accepted definition (Russell, 2012). Complicating matters further, emotions are often conflated with other affective constructs, such as moods and feelings, which are studied instead (Scherer, 2005). Due to a misunderstanding of the fundamental nature of emotions, research in the field can be limited to studying stereotypical expressions that are rarely encountered in real-life situations (Barrett and Satpute, 2019). Additionally, there have been 14 different ways identified to categorize emotions (Solomon and Stone, 2002). These factors have led some scientists to doubt the possibility of ever achieving an integrative theory of emotions (Niedenthal and Brauer, 2012). For recent discussions on the fundamental questions in emotion research, refer to the works of Gross and Barrett (2011) and Shackman and Wager (2019).

However, notable advancements have been made, and in order to gain a better understanding of what constitutes an emotion, it is valuable to examine the fundamental questions that the affective sciences must resolve to advance further. Reisenzein (2015) identified five questions that no current theory of emotion adequately addresses in a comprehensive and unified manner. These questions are: 1) the causal generation of emotions, explaining how emotions are triggered, 2) the effects of emotion on subsequent cognition and behavior, 3) the nature of emotion, describing what kinds of computational and mental states they are and how they are different from the other affective states, 4) the evolutionary and learning origins of the emotion system, and 5) the neural structures and processes involved in emotions. These considerations will be instrumental in selecting the approach to eliciting and analyzing emotional behaviors.

A crucial starting point to grasping the essence of emotion is to acknowledge its complex and multifaceted nature. It is widely accepted that emotions involve various components, including subjective experiences, behavioral expressions, physiological responses, and cognitive appraisals (Sander et al., 2018). Having acknowledged the different emotional components, it becomes crucial to comprehend the sequential order in which each component is triggered.

3.1.1 The causal generation of emotions

In the initial stages of learning about emotion theories, it is common to explore the historical development of different perspectives on emotion causation. Moors (2009) provides schematic illustrations of the various perspective for better understanding and visualizing the differences between them. The exploration usually involves examining approaches such as James-Lange (Figure 3.1A), Schacter-Singer (Figure 3.1B), appraisal (Figure 3.1C), and Barrett's theories (Figure 3.1D). Presented in chronological order, from primarily bodily and physiological to primarily appraisal-driven, it helps to understand the progression of ideas surrounding the emergent order of emotion components. In this context, the field of affective neuroscience offers a means to investigate the human brain and explore causal models of emotion, particularly regarding the potential causal role of bodily reactions in emotion (Sander, 2013). One notable approach in neuroscience is David Marr's three-level analysis of information-processing systems, consisting of computational, algorithmic, and implementational levels. Moors (2009) adopted this approach to examine different causational processes in emotions. She identified three key issues that theories aiming to explain emotions must address: elicitation, intensity, and differentiation. Moors concluded that only the appraisal theories adequately tackle these challenges. However, appraisal theories fall short in accounting for non-cognitive elicitation, indicating the need for further development in this area.

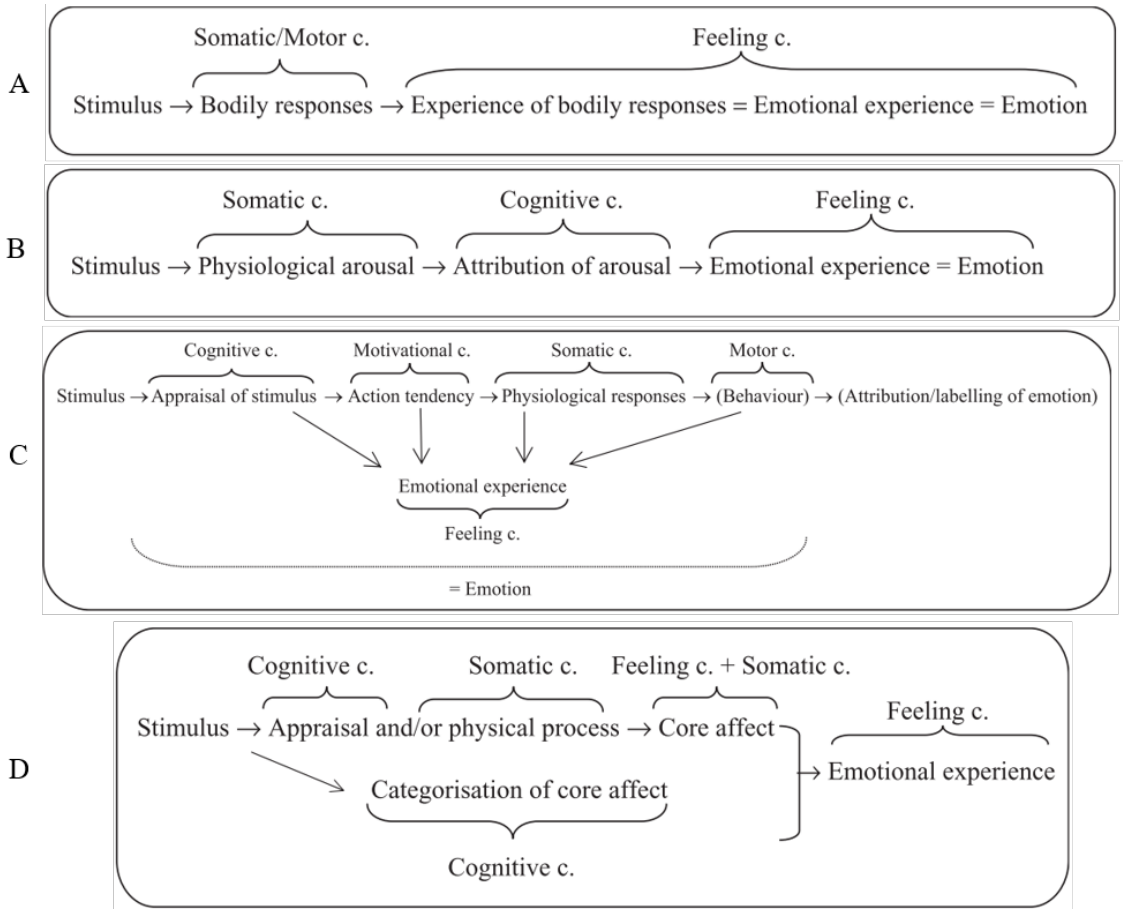


Fig. 3.1 Schematic illustration of theories illustrating the order of components (c.) in James' (A), Schacter's (B), appraisal (C), Barrett's (D) theories. Figure adapted from Moors (2009).

3.1.2 The effects of emotion on subsequent cognition and behavior

A reasonable consensus among researchers, as noted by Reisenzein (2015), has been reached regarding the functional nature of emotions. Emotions are now widely regarded as serving adaptive purposes, and researchers mostly agree on their functions. These functions include *attention-directing*, *informational*, and *motivational* aspects. The *attention-directing* function of emotions entails redirecting focus toward the triggering event and allocating central processing resources to analyzing and prioritizing these events. The *informational* function of emotions involves conscious or unconscious appraisal processes that provide valuable information to other subsystems within the organism, such as an increased heart rate to prepare for a response. Additionally, emotions can serve as a means of communication to convey information to other individuals, such as using aggressiveness to communicate a threat and avoid being attacked. Within this context, nonverbal signals, encompassing bodily movements, variations in vocal tone, and distinct gestures, can provide insights into an individual's discrete emotional states like sadness, anger, or joy. Importantly, the ability to convey and detect

emotions is not consistent and universal across various situations. Instead, it relies on the context, distinct physical actions, and the specific circumstances in which emotions appear, leading to variations in the qualitative characteristics of diverse bodily cues (Fourati and Pelachaud, 2018). Lastly, the *motivational* function of emotions relates to the adaptive effects of action goals, such as hedonistic desires to maximize pleasure and minimize pain.

3.1.3 The nature of emotion

In his recent work, Ortony (2022) has proposed three essential criteria for categorizing a mental state as an emotion. First, emotions require intentionality, as they are directed toward specific objects or individuals. This distinguishes emotions from core affect, which represents a background state characterized by a blend of pleasure and arousal but lacks a specific object of focus. Although emotions and core affect share common characteristics and can be described in terms of valence and arousal, the presence of a directed focus distinguishes emotions. It is crucial to avoid confusing these two concepts, as it has significant implications for measuring emotions. Merely observing changes in valence is insufficient for the emergence of emotions (Quigley et al., 2014). However, when individuals are drawn to a relevant object or situation, it triggers a synchronized response across various organismic subsystems (e.g., information processing, neurophysiology, behavior), enabling an effective response to the upcoming task (Scherer, 2005).

The second criterion for classifying emotions is their valence, which can be either positive or negative. An affective state that is characterized by indifference, lacking a positive or negative evaluation, does not qualify as an emotion. Emotions arise when explicit or implicit assessments are made to evaluate the significance of a situation. They are a response to the discrepancy between desired goals, standards, or concerns and the actual circumstances. In this sense, emotions can be seen as detectors of relevance (Damasio, 1994; Sander et al., 2003) that lead to specific action tendencies (Frijda, 2007).

The third essential criterion for emotion is that it involves conscious awareness and a subjective experience. This means that individuals are aware and can easily indicate the object or situation that triggered their emotional response. However, it is important to note that defining consciousness is complex, and some theories acknowledge that not all emotions are explicitly and unequivocally conscious. In certain cases, emotions may be processed in non-cortical structures of the brain (LeDoux, 1996). Nevertheless, it is important to note that these three characteristics offer a minimalistic understanding of emotions and do not provide a comprehensive answer to the question of ”What is an emotion?” as originally posed by James over a century ago. Instead, they serve

as defining features that distinguish emotions from other affective constructs (Ortony, 2022). This raises the question of what are these other affective constructs and what sets emotions apart.

Clear differentiation among various affective constructs would effectively address the issue of ambiguity and overlap between different affective constructs. Scherer (2005) delineated eight distinct features that can be used to differentiate these constructs, as summarized in Fig. 3.2. These specific features encompass event focus anchored in a specific event, appraisal-driven relevance for the organism, response synchronization triggering coordinated organismic responses; rapid adjustments to changing circumstances, behavioral impact through action tendencies; intensity, and duration features. Among the different constructs, emotions, and feelings are often misunderstood and sometimes even merged. Scherer (2005) posits that emotions involve a multicomponent process characterized by the key feature of the synchronized response of organismic subsystems, while feelings are single-component processes that solely represent the subjective experience related to an emotional episode. In comparison to mood, another frequently misconceived affective construct, emotions exhibit a clear event focus, greater intensity, and shorter duration.

Design features Type of affect	Event focus	Intrinsic appraisal	Transactional appraisal	Synchronization	Rapidity of change	Behavioral impact	Intensity	Duration
Preferences	VL	VH	M	VL	VL	M	L	M
Attitudes	VL	L	L	VL	L	L	M	H
Moods	L	M	L	L	M	H	M	H
Affect dispositions	VL	L	VL	VL	VL	L	L	VH
Interpersonal stances	H	L	L	L	VH	H	M	M
Aesthetic emotions	H	VH	L	MH	H	L	L–M	L
Utilitarian emotions	VH	M	VH	VH	VH	VH	H	L

Note: VL = very low, L = low, M = medium, H = high, VH = very high.

Fig. 3.2 Feature differentiation between different emotions and other affective constructs. Table adapted from Scherer (2005).

3.1.4 The evolutionary and learning origins of the emotion system

To what extent is the emotion system determined by evolutionary architecture versus learned mechanisms throughout the lifespan? According to Darwin (1872), emotions are inherited and shared among different species, suggesting a universality of expressed emotions. He wrote, *"the young and the old of widely different races, both with man and animals, express the same state of mind by the same movements"* (Darwin, 1872, p.352). However, this view does not fully account for the learned modifications of emotional experiences as a result of classical conditioning (e.g., LeDoux, 1996). For instance, a snake might initially be perceived as a neutral stimulus for a child. But after being exposed to movies triggering strong fear responses or experiencing a frightening

encounter with a dangerous snake, the child may develop a strong emotional response to snakes, turning them into highly arousing stimuli.

The dichotomy between inherited and acquired emotion has ignited passionate debates within the field of affective sciences. Paul Ekman and Lisa Feldman Barrett are recognized as prominent contemporary figures representing these conflicting research perspectives in emotion research. Their divergent views are not limited to intense debates and discussions in scientific research publications but also extend to popular journals such as the New York Times (Barrett, 2014) and Huffington Post (Ekman, 2014).

In essence, Ekman's theory of basic emotions, inspired by Darwin's work, proposed the existence of fundamental emotions that shape human behavioral expressions. To examine Darwin's notion of universal innate features shared across cultures, Ekman conducted research in a preliterate society in New Guinea, devoid of Western cultural influences. The primary objective of the study was to assess the capacity of both children and adults in the tribe to accurately decode and classify facial expressions. The results demonstrated that the tribe members were able to correctly identify and categorize emotions expressed through facial expressions above chance levels, providing support to the idea of the universality of emotions (Ekman and Friesen, 1971). Accordingly, the defining features of basic emotions encompass specific patterns of facial muscle activation (known as action units), unique bodily expressions, and distinct physiological responses (Ekman and Cordaro, 2011). Another argument is that congenitally blind individuals have the ability to spontaneously smile and express emotions without ever having seen a smile, further confirming that facial expressions are innate without the need for learning through imitation (Galati et al., 1997).

In her theory of constructed emotions, Barrett (2017) critiques the essentialist perspective and asserts that basic emotions were not discovered by scientists but rather stipulated. Contrasting the forced choice experimental setting employed by the research of Ekman and Friesen (1971) in tribes, research indicates that utilizing an open-ended context significantly reduces the accuracy of facial expression recognition to chance levels (Betz et al., 2019). Furthermore, it is a fundamental error to make a reverse inference without considering contextual factors and relying solely on stereotypical facial expressions, which exhibit significant variations among individuals (Barrett and Satpute, 2019). This variation supports the concept of degeneracy, indicating a complex, many-to-many relationship between elicitors and emotional expressions (Barrett and Satpute, 2019). The same applies to physiological distinctiveness, as there is a notable overlap in autonomic activations that are not specific to distinct discrete emotions (Siegel et al., 2018; Levenson, 2003). Finally, the argument regarding congenitally blind individuals is inconclusive, as research suggests that blind infants, children, and adults utilize

only a subset of facial muscles that the theory of Basic Emotions posits (Barrett et al., 2007). There is still a need for further understanding regarding how the experiences and learning of blind individuals through other modalities, such as touch and sound, may influence or contribute to their ability to produce facial expressions.

The brief summary and comparison we presented here regarding the theories of basic emotions and constructed emotions barely scratched the surface of the vast array of other theories that explain the role of the evolutionary origins of the emotional system and the environmental circumstances. To do justice to the diverse range of theoretical perspectives, Gross and Barrett (2011) proposed a continuum of psychological theories, depicted in Fig. 3.3, which spans from theories emphasizing basic emotions as fully evolutionary to theories highlighting emotions as mere social constructions. In this dissertation, we adopt the functionalist perspective in which the understanding of emotions and their adaptive value corresponds to an environmental context that guides an individual's behavior, influencing the subjective experience and cognition and eliciting physiological responses to effectively respond to environmental challenges (e.g., Barrett, 2017; Campos et al., 1989; Frijda, 2007; Parrott, 2001).

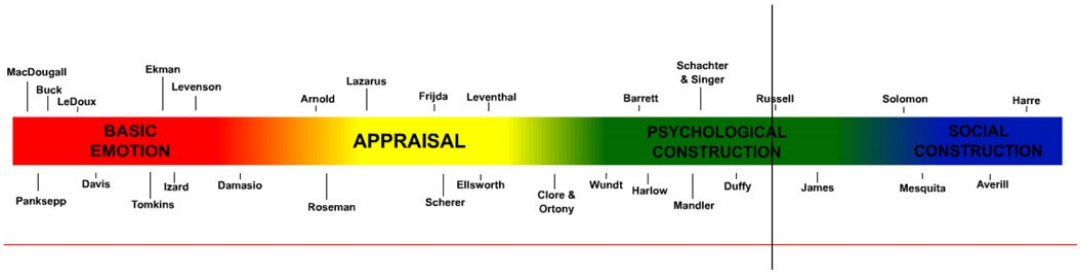


Fig. 3.3 Continuum of psychological research theories of emotions. Figure adapted from Gross and Barrett (2011).

3.1.5 The neural structures and processes involved in emotions

In the ongoing scientific discussions about brain organization and the neural basis of emotional processing, two contrasting approaches have emerged (Lindquist et al., 2012). One perspective, known as the locationist approach, posits that discrete emotions are represented by specific regions in the brain Panksepp and Watt (2011). In contrast, the psychological constructionist approach suggests that emotions and mental states do not have dedicated brain regions or neural circuits. Instead, they arise from dynamic coalitions of networked brain areas that work together to integrate emotional functions without specialized localization (Pessoa, 2008). In their study, Saarimäki et al. (2016) conducted experiments using various emotion-inducing stimuli to investigate the neural signatures associated with six basic emotions. By employing fMRI and applying a multivariate pattern analysis, the researchers found consistent and distinct

neural patterns corresponding to specific emotions across different experimental conditions. These emotion-specific neural signatures were observed to be shared among individuals, highlighting common underlying mechanisms associated with discrete emotions. However, Clark-Polner et al. (2017) presented a statistical counterargument to the findings of Saarimäki et al. (2016) regarding the neural fingerprints of basic emotions. They argued that the pattern classification results obtained from the study could be considered statistical abstractions that may not necessarily reflect the true nature of emotions in the brain. Thus, the question about the neural foundation of emotional processing remains unresolved.

In the last two decades, significant research evidence has surfaced suggesting that emotional processing doesn't solely rely on cortical brain structures (LeDoux, 1996; LeDoux and Pine, 2016). Instead, alternative structures are involved to achieve quicker behavioral outcomes. This discovery, along with its crucial implications for motor control, will be discussed in greater detail in the following section.

3.2 The influence of emotions on the human motor control system: insights from Neuropsychology

The functioning of the human motor control system is intricately intertwined with the emotional state of the individual. Following the publication of his influential work "The Expression of the Emotions in Man and Animals" (Darwin, 1872), which aimed to demonstrate the shared evolutionary trajectories of animals and humans, Darwin described how emotions are expressed through posture and body movements and remarked the universal nature of emotional expression among conspecifics. However, in a recent publication, Rosenbaum (2010) delivered a persuasive appeal to the scientific community dedicated to studying human motor control, urging them to explore the intricate relationship between emotions and motor control. This call to action was motivated by the remarkable dearth of research in this domain, despite the promising findings obtained from experiments involving monkeys with lesioned motor cortex. Specifically, when the monkey was calm, it was unable to utilize its upper extremities. However, on certain occasions, when the monkey experienced emotional distress and was upset, it was occasionally able to regain the use of its limbs (Rosenbaum, 2010). Another illustrative case involves a patient named Louis Victor Leborgne, who, as a result of his condition, was only able to produce the syllable "TAN." But when the patient experienced episodes of rage, as he suddenly gained the ability to articulate a single word or a short phrase (Mohammed et al., 2018). Yet, emotions do not possess healing superpowers that enhance and amplify impaired efferent neural signals to the periphery. Instead, emotional motor control uses distinct pathways compared to the pathways used in an

intentional context. To discern these differences, it is crucial to identify the occurrence of double dissociation.

Coined by Teuber (1955), the term double dissociation carries great significance in the field of clinical neuropsychology as a powerful tool for advancing the understanding of brain functioning. In essence, double dissociation helps identify two different cognitive and neural processes that are functionally independent and can operate separately from each other, despite being part of the same overall system (Campbell et al., 2019). Through the identification of two contrasting patient cases, researchers draw robust conclusions about the specificity and independence of the two neurocognitive processes. In one case, where a patient has a lesion of the central or peripheral nervous system, the first neurocognitive ability is impaired while the second remains intact, and in another case, the first ability remains intact while the second is impaired. An illustrative example that demonstrates double dissociation can be observed when examining the differing effects on neurocognitive deficits in patients who display authentic and pretentious smiles.

The distinction between a genuine smile and a fake smile lies in the subtle differences in facial muscle activation and changes in a smile's appearance (Ekman and Friesen, 1982). Findings in the motor control literature provide evidence supporting the existence of distinct neural motor control processes for genuine emotional smiles (i.e., spontaneous), in contrast to fake smiles (i.e., intentional) Campbell et al. (2019). Fig. 3.4 features the photographs of two patients who are presented as case examples (Rinn, 1984). The top row shows a patient having a tumor in the face representation region of the right primary motor cortex. The bottom row demonstrates individuals suffering from impaired extrapyramidal motor functions as a cause of subcortical cerebral infarction. In the photograph at the top left, the individual is instructed to produce a smile, revealing a unilateral loss of voluntary muscle activation of the left side, i.e., left facial paresis. Conversely, in the photograph at the top right, the same individual genuinely smiles, demonstrating bilateral activation of facial muscles and indicating intact peripheral muscle activation. In contrast, the photograph at the bottom left depicts an individual who has not experienced a loss of voluntary motor control over their facial muscles in a resting state. However, in the photograph at the bottom right, a left facial paresis is evident during a spontaneous smile. This double dissociation provided evidence supporting the differentiation between intentional (volitional) and spontaneous (emotional) facial motor control (Campbell et al., 2019; Rinn, 1984; Töpper et al., 1995). But what specific factors distinguish spontaneous emotional smiling from intentional smiling in terms of motor command and subsequent muscle activation?

The prefrontal cortex, situated in the frontal lobe of the brain, plays a crucial role in

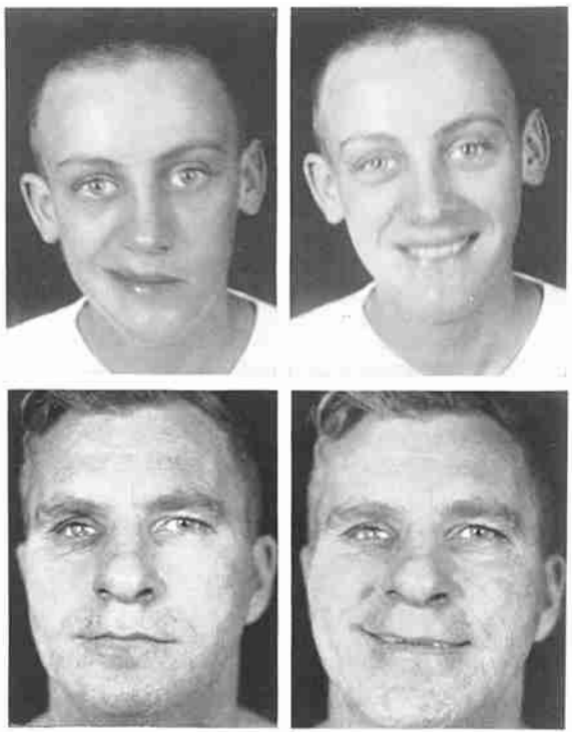


Fig. 3.4 Evidence for the double dissociation of intentional and emotional motor control. Figure adapted from Rinn (1984).

attention, response inhibition, and working memory, and is essential for the process of planning voluntary behaviors (Miller et al., 2002). Nevertheless, the presence of intentional motor commands is not essential for executing movements, as emotions can elicit spontaneous movements through the emotional motor pathways that directly involve the amygdala, bypassing the prefrontal cortex (LeDoux, 1996). Indeed, in the absence of intentional motor command, the amygdala and the subcortical motor pathways have the ability to modify and regulate facial expressions (Gothard, 2014). This demonstrates that the generation of intentional and emotional facial expressions involves two separate neural mechanisms. When these mechanisms are impaired, they give rise to specific neurological conditions known as volitional facial palsy and emotional facial palsy, respectively (Campbell et al., 2019).

The differentiation between intentional and emotional neural mechanisms was observed in the context of speech production as well. The intentional motor system communicates with motoneurons through Broca's area and the motor cortex, while the emotional motor system can directly communicate with motoneurons through the periaqueductal gray and the nucleus retroambiguus (Holstege and Subramanian, 2016). These findings highlight the complex interplay between intentional and emotional aspects of motor control, demonstrating that the emotional motor control system not only has the ability to modulate the motor commands sent by the intentional motor control system but can also generate movements independently. Acknowledging the mechanisms of emotional

motor control provides significant benefits in unraveling the complex nature of human social behavior. By recognizing these mechanisms, we gain a deeper understanding of the social implications that emerge in diverse contexts, encompassing both small groups and larger scales.

Summary of Chapter 3

- Generally, for an emotion to be triggered, some form of **appraisal** is typically necessary.
- Emotion serves as a **relevance detector** in an individual's surroundings.
- Emotions serve several functions, including **directing attention, allocating cognitive resources**, and, if necessary, **motivating** action.
- Emotions stand apart from other affective states due to their distinct characteristics. They are typically elicited by a **clear antecedent**, have a **relatively short duration**, and **activate** various **multi-component processes** encompassing behavior, physiology, and cognition. These processes prepare individuals for potential **action or response**.
- There are diverse approaches to understanding emotions, and the basic emotions approach, which takes an **essentialist perspective**, has received criticism for its focus on stereotypical expressions. As a result, alternative **functional views** are emerging to provide a broader understanding of the complexities of emotions.
- The essentialist perspective, which suggests the possibility of making reversed inferences based on body posture, physiological activation, and facial expression, **is not supported by the available data**. Instead, the evidence suggests a **many-to-many mapping**, indicating that multiple emotions can be associated with various bodily and physiological states.
- Neurological evidence indicates the presence of an **alternative neural pathway** that allows emotions to be processed and **directly influences motor control of the body**, bypassing the cortex.

CHAPTER 4

General problematics

Based on the literature discussed in previous chapters, we have found compelling evidence supporting the integration of research fields related to joint action and emotion. However, despite the potential synergies between these domains, certain issues impede their seamless integration. In this chapter, our objective is to explore these issues with greater depth and shed light on how resolving them can contribute to the expansion of existing knowledge.

Group emotions can emerge as a result of emotional contagion. In this context, the processes of interpersonal synchronization (Burgoon et al., 1995) and mimicry (Chartrand and Lakin, 2013) serve as facilitative mechanisms that allow to capture and reflect individuals' emotions. These processes enable the alignment of emotional expressions and behaviors between individuals, fostering the perception and understanding of emotions within social interactions (Hatfield et al., 1994). Similar to the synchronization of Huygens pendulum clocks, nonverbal communication plays a crucial role in establishing the exchange of information between individuals through nonverbal channels. This exchange leads to shared emotional experiences within a group. Specifically, nonverbal cues influence the movement patterns of individuals, giving rise to the emergence of emotional contagion (Parkinson, 2020) and resulting in greater levels of empathy (Sonnby-Borgström, 2002). Empathy plays a foundational role in the process of experiencing emotional contagion, as it serves as a building block for the phenomenon.

Decety and Jackson (2004) proposed three functional and intertwined components that contribute to the experience of empathy in humans, setting them apart from non-human species. These components include i) perception-action coupling, which results in shared representations between individuals in their environment; ii) emotion regulation mechanisms that enable the differentiation between oneself and others, and iii) perspective taking, which allows individuals to adopt the subjective viewpoint of others, enabling them to gain valuable insights into the experiences and inner world of those people. The three functional components of mimicry embody the process of emotional

contagion by automatically aligning with others' experiences, facilitating the sharing of emotions, and thereby enabling the transmission and resonance of each other's emotional states (Hatfield et al., 2011). Ultimately, emotional contagion enables experiencing strong collective emotions and gives rise to collective effervescence (Durkheim and Fields, 1995).

Several empirical studies have shed light on the potential occurrence of collective effervescence by investigating how interpersonal synchrony contributes to affective outcomes. Research by Bernieri et al. (1988) revealed that the synchronous interaction of a child with its mother, as opposed to dyssynchronous interaction, was linked to a greater display of positive affect. Similarly, Rabinowitch and Cross (2019) found that synchronous interaction enhanced the recognition of happiness and sadness in ambiguous facial expressions and led to increased positive affect and decreased negative affect in musically untrained children. Zhang et al. (2016) observed an enhanced emotional response when individuals engaged in finger tapping with a virtual partner, particularly in stable patterns such as in-phase and anti-phase. Valdesolo and DeSteno (2011) manipulated rhythmic movement in synchrony, accompanied by explicit awareness rather than automatic mimicry, and discovered that synchrony has the ability to modulate emotional responses and elicit compassion and altruism. Vacharkulksemsuk and Fredrickson (2012) measured emotions following synchronized movement and found that it increased self-other overlap and positive emotions. Feniger-Schaal et al. (2021) reported that engaging in synchronized activities led to more enjoyment, reduced negative affect, and increased positive affect. Taken together, these findings provide evidence for the emotional function of engaging in synchronized movements with others.

Thus far, we have not examined the antecedents and factors that precede or contribute to interpersonal synchronization. The antecedents encompass various factors, including but not limited to, the similarity in individuals' propensity for prosocial behavior (Lumsden et al., 2012), similarity in personality traits (Słowiński et al., 2016), and anthropometric characteristics like stride length during walking (Nessler and Gilliland, 2009). Furthermore, it is important to consider affective antecedents, including perceived attractiveness (Zhao et al., 2015), as well as broader factors such as mood and emotion (Chartrand and Lakin, 2013), which also hold relevance in facilitating interactions. The existing literature exploring the directionality of the influence of emotions on interpersonal synchronization is limited. In a concise manner, we outline the key issues that demand specific attention.

First and foremost, there is a significant challenge in social neuroscience research in effectively *inducing naturalistic emotions*. Various procedures employed for emotion inductions, such as watching movie clips, listening to music, or acting out emotions, are

plagued by low ecological validity (Levenson, 2003). To successfully induce alterations in emotional states, researchers have employed various methods. For example, to induce changes in emotional states, Kuhbandner et al. (2010) and Hasson et al. (2004) utilized a library of films, specifically using emotionally arousing scenes excerpted from renowned movies. Cheong (2019) had participants watch character dramas on television, while Fujiwara and Daibo (2018) systematically manipulated emotions by utilizing video clips specifically chosen for the Japanese population. Furthermore, in some cases, participants are asked to enact specific emotions as part of the experimental procedure (Chang et al., 2019; Varni et al., 2010). By contrast, some researchers have chosen to enhance ecological validity by opting for a more naturalistic context, such as dyadic conversations (e.g., Main et al., 2016; Paxton and Dale, 2013; Tschacher et al., 2014). Nevertheless, although these methods offer improved ecological validity, ensuring experimental control becomes more complex. Alternative approaches that promote naturalistic settings include utilizing interactive game tasks to exclusively measure negative emotions such as frustration (Algumaei et al., 2023) or assessing the enjoyment experienced by an audience during a concert while focusing solely on positive emotion pleasure (Chabin et al., 2022). However, in this context, the obtained results are confined to a single emotional state, and it remains uncertain how different emotions may yield varying effects. In summary, the initial significant challenge in the study of emotions lies in developing a method that can systematically induce distinct emotions with high ecological validity within a repeated measures experimental design.

The second issue arises from the tendency to examine social interactions *unimodally*, focusing solely on physiology, psychology, or behavior independently. However, it is important to recognize that social interactions are an inherently multimodal process, encompassing not only verbal communication but also nonverbal behavior, facial expressions, vocalizations, and even physiological resonance (e.g., Louwerse et al., 2012; Palser et al., 2021; Tatarian et al., 2022). These diverse elements actively coordinate and convey information during social interactions, contributing to their dynamic nature and complexity. To provide additional support for this perspective, certain phenomena, such as the enfacement illusion, demonstrate that specific reactions can only occur within a multimodal context (Paladino et al., 2010). These experiences are intertwined with affective outcomes (Maister et al., 2013) and emerge as a result of embodied resonance, where there is a partial reenactment of the observed sensorimotor events (Barsalou, 1999). Neglecting the multimodal nature of social interactions and solely focusing on isolated modalities, such as physiology, psychology, or behavior, overlooks the intricate interconnectedness and holistic nature of human communication and interaction (Mayo and Gordon, 2020). Moreover, emotions are complex and multifaceted phenomena (Sander, 2013; Scherer, 2005), necessitating the integration of a multimodal

approach to comprehend and recognize emotions effectively (Ross and Atkinson, 2020; Quan et al., 2021). Consequently, the second challenge lies in adopting a multimodal approach with adaptive methodological tools that allow for simultaneous investigation of the emotional impact on behavior, physiology, and cognition.

The third issue pertains to the predominant focus of many research paradigms on the examination of *dyadic interactions*. However, focusing solely on dyadic interactions provides limited insight into the broader dynamics of large-scale coordination that occur in everyday life situations (Tarr et al., 2014; Tunçgenç et al., 2021). Furthermore, by solely focusing on dyadic studies, the emergent processes occurring at the group level are overlooked (Dale et al., 2020; Fujiwara, 2016; Keltner and Haidt, 1999). Specifically, synchronization at the group level transcends being a mere aggregation of individual elements or pairwise relations (Tomashin et al., 2022). Instead, it involves the evolution of a collective entity, sometimes referred to as a "superorganism" (Emerson, 1939), which challenges the conventional understanding of an individual within the system. In this context, the system itself assumes the characteristics of a new, distinct, and constantly evolving and redefining itself as a living entity. This necessitates investigating the dynamics of entry into and withdrawal from synchrony (Mayo and Gordon, 2020). Additionally, understanding the process of coupling and uncoupling, as examined by Dumas and Fairhurst (2021), provides insights into group homology—namely, how the geometry of group interaction, known as topology, evolves and changes over time (Zhang et al., 2020). Collectively, the third significant challenge entails transitioning from dyadic research to group-level investigations to gain a deeper understanding of the dynamic and emergent processes that manifest in interactions within groups.

Part III

RESEARCH THEMES AND QUESTIONS

CHAPTER 5

Research themes and questions

Acknowledging and exploring the significance and influence of emotions in human joint action is essential for a more holistic understanding of how individuals coordinate their actions, communicate effectively, and establish successful collaborative relationships. The related works section of this dissertation elucidated that although emotions are central to human functioning, their precise role in human social interaction remains somewhat elusive. The challenges can be succinctly summarized as follows: the absence of sufficient theoretical justification, discrepancies in the utilization of analytical methods, and a dearth of empirical evidence regarding the impact of emotions on multimodal, group interpersonal synchronization. A primary concern lies in the limited ecological validity of methods employed to induce emotions, thereby compromising the obtained results. To address these challenges, this doctoral dissertation is structured around three open-ended research themes, providing a comprehensive investigation and exploration of each theme.

Theoretical theme: Emotions in human joint action

The first theme focuses on the **theoretical** aspects. Within this broad theme, our objectives are to provide an overview of the current state of knowledge regarding human joint action and emotion and to identify the reasons behind the limited incorporation of emotion in research on interpersonal synchronization. Understanding the interplay between these two research areas is essential for advancing our understanding of human social interactions. Despite traditionally being explored independently, recognizing and establishing connections between joint action and emotion holds significant potential. We accumulate theoretical and empirical evidence to conceptualize joint action and emotion.

> **Research question № 1**: How does integrating emotion research into the study of human joint action contribute to a deeper understanding of interpersonal synchronization processes?

Methodological theme: Operationalization of interpersonal synchronization

The second theme focuses on the **methodological** aspects. In this theme, we delve into the literature on the evaluation of interpersonal synchronization, exploring the divergent conceptualizations of this phenomenon across various disciplines. Additionally, we compare and contrast different analytical techniques used for data with distinct characteristics. While measuring interpersonal synchronization can sometimes be reduced to assessing unison, the objective of this theme is to emphasize the importance of approaching it as a dynamic process.

> **Research question № 2**: Which methodological approach yields the highest accuracy and reliability in measuring interpersonal synchronization during social interactions?

Experimental theme: Effects of emotions on interpersonal synchronization

The third theme of our research focuses on **experimental** investigations. In this theme, we conduct two original studies to examine the impact of emotions on interpersonal synchrony across different experimental settings. This theme encompasses two key research questions. Firstly, as part of my PhD research, I propose an innovative approach to naturalistically induce emotions while ensuring the ecological validity of the emotion induction method and maintaining a high level of experimental control. This method aims to provide a more realistic emotional experience for participants. Secondly, we aim to explore the nuanced effect of contextual factors on how emotions function within both unstructured and structured experimental contexts. By considering the influence of context, we can gain a deeper understanding of how emotions shape interpersonal synchrony in various situations.

> **Research question № 3**: What methodological principles should be upheld to effectively induce emotions with both high ecological validity and experimental control in research settings?

> **Research question № 4**: Do emotions influence interpersonal synchronization within an unstructured and structured experimental context?

Part IV

PERSONAL CONTRIBUTIONS

Illustration of the themes of this dissertation, their corresponding publications, and the details of the degree of my contribution[1]. according to the Contribution Roles Taxonomy (CRediT) to specific roles during the experiment and publishing process (i.e., Lead - the contributor was one of the lead contributors; Supporting - the contributor was one of the supporting contributors, not a lead; Equal - the contributor was neither a lead nor a supporting contributor, all contributors were equal).

[1] https://jats.nlm.nih.gov/archiving/tag-library/1.2/attribute/degree-contribution.html

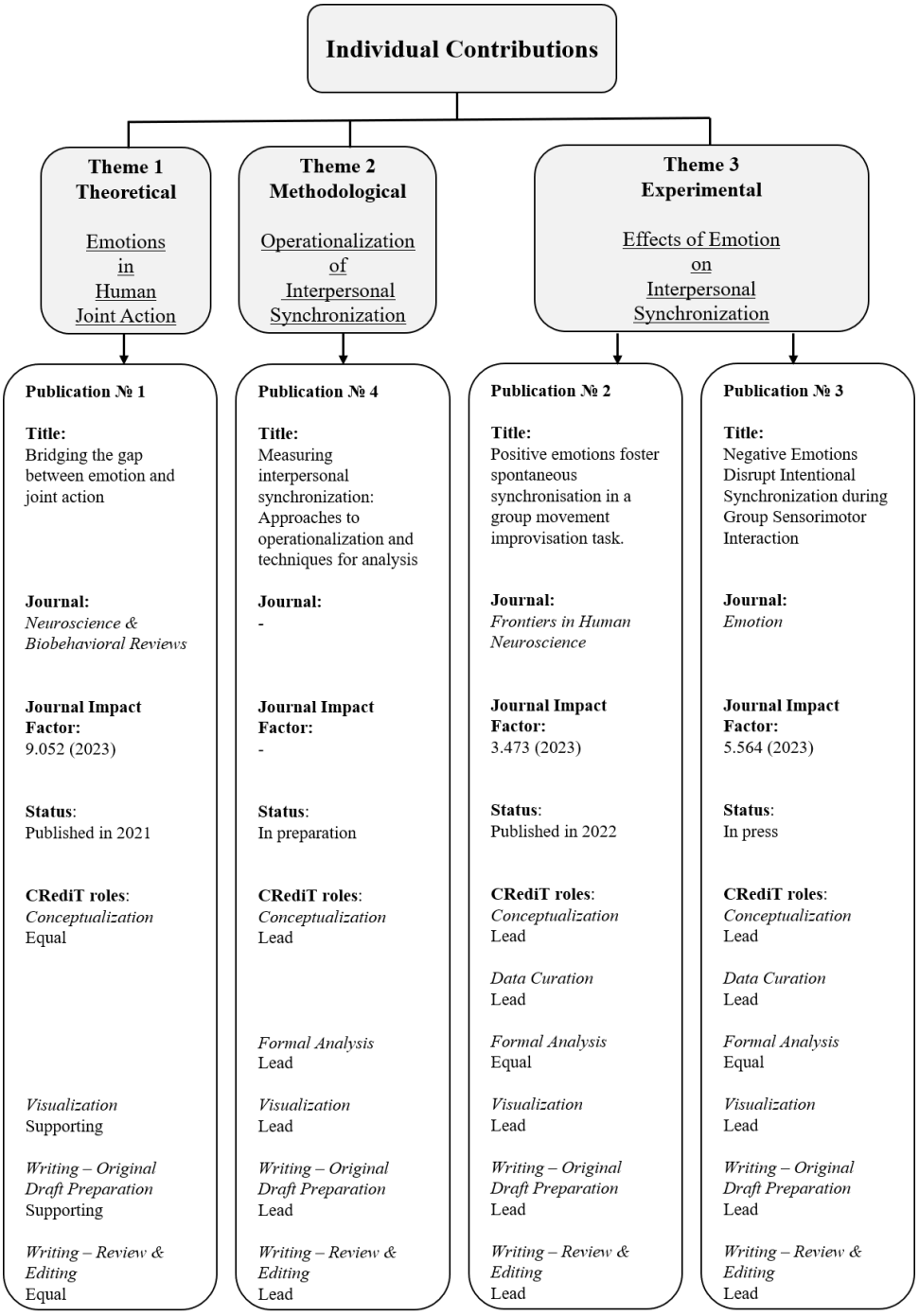


Fig. 5.1 Depiction of individual contributions in the present doctoral dissertation.

CHAPTER 6

Theme 1: Theoretical

This chapter presents Publication № 1: Bieńkiewicz, M. M. N., **Smykovskyi**, A. P., Olugbade, T., Janaqi, S., Camurri, A., Bianchi-Berthouze, N., Björkman, M., Bardy, B. G. (2021). Bridging the gap between emotion and joint action. Neuroscience and Biobehavioral Reviews, 131, 806–833. https://doi.org/10.1016/j.neubiorev.2021.08.014

The primary focus of the first publication is to provide emerging evidence for the need to interconnect the fields of emotions and joint action. First, we overview the field of joint action, the social implications of acting together, the underlying neural mechanisms, and delve into models of interpersonal synchronization.

Second, we examine current models of emotion, focusing on group-oriented conceptual frameworks. In addition, our aim is to synthesize the manifestation of emotion through various modalities (e.g., facial expressions, behavior, and physiology) and to consider the multiagent contexts. In this light, the clinical findings obtained from individuals diagnosed with schizophrenia and Autism Spectrum Disorder, representing populations with socio-motor interaction deficits, offer valuable insights into the significance of impaired emotion detection in the dynamics of social interaction.

Third, we substantiate our argument by incorporating evidence derived from the domains of Human-Computer and Human-Robot Interactions, encompassing diverse populations and contextual settings. The focus of this investigation is on developing an understanding of the guiding principles that enable non-human agents to effectively engage in real-time socio-motor interaction with humans.

Lastly, drawing upon the accumulated theoretical and empirical evidence highlighting humans' intrinsic tendency for attunement to one another, particularly through body movements, our objective is to gain a better understanding of the interplay between joint action and emotion and propose directions for future research.

The Neuroscience and Biobehavioral Reviews journal was chosen for this publication. Among the key subject areas of interest listed on the website are: Neuropsychology and

Physiological Psychology, Cognitive Neuroscience, Experimental and Cognitive Psychology, Behavioral Neuroscience. Interest in original review articles examining the connection between psychological processes and behavior relevant to Behavioral Neuroscience aligned with that of our study, which focused on the theoretical underpinnings of human joint action and the often overlooked role of emotions.

Neuroscience and Biobehavioral Reviews 131 (2021) 806–833

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Bridging the gap between emotion and joint action

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ABSTRACT

Our daily human life is filled with a myriad of joint action moments, be it children playing, adults working together (i.e., team sports), or strangers navigating through a crowd. Joint action brings individuals (and embodiment of their emotions) together, in space and in time. Yet little is known about how individual emotions propagate through embodied presence in a group, and how joint action changes individual emotion. In fact, the multi-agent component is largely missing from neuroscience-based approaches to emotion, and reversely joint action research has not found a way yet to include emotion as one of the key parameters to model socio-motor interaction. In this review, we first identify the gap and then stockpile evidence showing strong entanglement between emotion and acting together from various branches of sciences. We propose an integrative approach to bridge the gap, highlight five research avenues to do so in behavioral neuroscience and digital sciences, and address some of the key challenges in the area faced by modern societies.

1. General introduction

We thrive on being surrounded by others; we wither when isolated (Baumeister and Leary, 1995). The quantity and the quality of our social interactions are one of the most robust predictors to both how well and how long we live, beating the predictive power of exercise or obesity (Holt-Lunstad et al., 2010). Our brains have been carved by evolution to act together with others towards long-term mutual goals, by emergence of 'self'-transcendental emotions as opposed to immediate and egoistic benefits (Stellar et al., 2017). These emotions (i.e., compassion, gratitude, or awe) exclusively promote coalitional behavior such as caretaking, cooperation and coordination. For these reasons, moving in unison with others is the firmest of social ties, a superglue, pushing us as a group towards more ambitious goals and performance outcomes as opposed to acting as individual units (Duranton and Gaunet, 2016; Hasson et al., 2012; Marsh et al., 2009; Salmela and Nagatsu, 2017; von Zimmermann and Richardson, 2016). Army drills based on marching together bring a feeling of affiliation and facilitate group performance (McNeill, 1995), just like the Haka dance in a rugby match pumps up the morale before meeting the enemy and perceptually diminishes the strength of the rival (Clément, 2017; Fessler and Holbrook, 2014). We appraise being a member of a larger group ('tribe') by aligning our actions with others (Tsai et al., 2011) to show we like them, we care about them and we are ready to work with them (Mogan et al., 2017; Parkinson, 2020). According to anthropological and behavioral research, a group that chants and dances well together also hunts well (von Zimmermann and Richardson, 2016). Throughout centuries, political and religious power holders have engaged crowds during rallies by using repetitive gestures or vocal expressions (Heinskou and Liebst, 2016; Lukes, 1975). Such rituals (for instance the Nazi salute during May Day rally, cf. Allert, 2009) put normative pressure on individuals with the purpose of bringing up a certain collective thought and feeling, captured by a classical, yet poorly understood in neuroscience, sociological concept of 'collective effervescence' (Liebst, 2019; Pickering, 2020). The social morphology of being in a crowd is viewed as essential for motor and emotional synchrony through entrainment of rituals (Borch, 2015; Collins, 2004) with the emergence of contagion hot spots ('transmitters') being the essence of collective effervescence (Liebst, 2019; Zheng et al., 2020).

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Surprisingly, although our social interactions are highly intertwined with emotions we convey or receive, emotions and joint actions are primarily analyzed and modeled by different branches of science, and are usually described separately from each other (Salmela and Nagatsu, 2017). Most models of emotion are individualistic and do not explicitly consider the social context of interacting with others, recently identified as the 'dark matter' of modern neuroscience (Schilbach et al., 2013). Exceptions exist in research on empathy (e.g., the model of therapist - patient relation by Koole and Tschacher, 2016), and in research dedicated to movement expression and propagation in arts, such as musical ensembles or dance performance (e.g., Alborno et al., 2015; Basso et al., 2021; Camurri et al., 2011; Chabin et al., 2020; Jola et al., 2013). However, the "acting together" component has not yet been tackled (Butler, 2017; Goldenberg et al., 2016; Mayo and Gordon, 2020).

Reciprocally, human synchronization models, which dominate the joint action research, are not usually inclusive of the emotional state of agents and the manifestations of emotions or other affective components in the way agents move to achieve an optimal outcome (Wallot et al., 2016a; Wolpert et al., 2003). This urgency to address emotional social interaction aspects was recently recognized by Shamay-Tsoory et al. (2019) in their social alignment model, which incorporates the emotional component of group behavior. The scarcity of research is quite surprising, taking into consideration that both self-transcendent emotions and cooperation evolved together as strong features of humanity and contributed greatly to human dominance in the animal kingdom (McNeill, 1995).

In this paper, we zoom into a large body of literature in order to give a synthetic review of the current state of the art on emotion and on joint action, currently two separate strands of research[1]. We present evidence showing how these fields are intertwined, and in need of marriage to create a more interdisciplinary and ecologically relevant branch of science. Understanding how we feel impacts the way we act together, and how we act together impacts our emotions, is a societal and scientific challenge of the utmost importance (Barrett, 2017a; Feldman Barrett and Finlay, 2018; Salmela and Nagatsu, 2017; Shamay-Tsoory et al., 2019; Wallot et al., 2016b; Wolpert et al., 2003). As posited by Salmela and Nagatsu (2017), we argue that the emotional component can reveal a lot about the prediction of actions of others, but also about the unfolding of joint acts and their outcomes. We propose a pathway for updates of current models on joint action, such as synchronization, that could be a start to a more integrative approach. We intend to encourage the scientific community to join this conversation, by prompting potential research questions, revise current models of emotion and joint action across neuroscience, computer sciences and social sciences, and to move towards more integrative, social approaches (e.g., Hasson et al., 2012; Hoemann and Feldman Barrett, 2019).

Throughout our review, and in the future directions Section 5, we show evidence that witnesses how the stem of this new research avenue is now shaping the future of human machine interfaces (e.g., robotics, interactive art systems, embodied social media). We believe this new avenue will lend itself to informing occupational health; in promoting efficient and human-friendly working environments and workflows (be it digital or physical) - on a micro-scale, but also crowd management during sport, public and emergency events - on a macro-scale.

2. Joint action: humans act together

2.1. What is joint action?

Joint action can be regarded as any form of socio-motor interaction whereby two or more individuals coordinate their actions in space and time to bring about a change in the environment. Joint action depends on the following mechanisms: joint attention, representations of others, action prediction and coordination, as well as awareness of oneself and the outcome of the actions of others (Sebanz et al., 2006). Acting together can be emergent or planned and it encompasses the level of intentions, action plans and movements (Knoblich et al., 2011). There is a great variety of terms used by scientific communities in reference to the phenomenon itself: joint action (Sebanz et al., 2006), interpersonal coordination (Mayo and Gordon, 2020; Vicaria and Dickens, 2016), interpersonal adaptation (Burgoon et al., 1995), nonverbal adaptation (Bodie et al., 2016) or even social interactions (Hasson and Frith, 2016). Furthermore, scholars have often offered narrow typologies for joint action subclasses such as physiological or behavioral synchrony and behavioral matching (Mayo and Gordon, 2020), interactional synchrony and behavioral matching (Bernieri and Rosenthal, 1991), mimicry and imitation (Chartrand and Bargh, 1999). Differences in the terminology used by researchers usually stem from stressing and developing models of a particular aspect of socio-motor interaction. For example, Jarrassé et al. (2012) distinguished divisible, interactive and antagonistic tasks, focusing on the objectives and roles each interactant follows (see Table 1). Similarly, Clark (1996) and Toma (2014) both accounted for the temporal relationship of interactions and concentrated on perceptuomotor aspects of interaction during communication. Burgoon et al. (1995) proposed a more holistic framework of different dimensions (e.g., directedness, timing, measure of behavioral change, intentionality, etc.) to study dyadic adaptation (see Fig. 1).

What remains uncertain in this classification is the required number of characteristics that need to be satisfied for interaction to be regarded as joint action, and its sub-level type, and whether the individual change occurs prior, during or after the interaction (Burgoon et al., 1995). Importantly, joint action does not automatically imply cooperation; it can also indicate competition in terms of individual performance within the group, depending on whether action goal is driven by individual gain (be better as a unit than others) versus collective gain (be better as a group than others) (Tuomela, 2011), leading to multiple possible patterns of coordinated dyadic and group joint action. Table 1 presents an overview of the major sub-types of socio-motor interaction discussed further in this review.

2.2. Models of human group synchronization

As a specific branch of joint action research, the synchronization of a group of agents - such as humans and other animals – or by robotic or digital agents, all underlying the achievement of a common goal, is a robust example of dismissing the emotion component during socio-motor interaction. The state of the art in this domain spans over several scientific disciplines including ethology (Couzin et al., 2005) cognitive and movement neurosciences (e.g., Alderisio et al., 2016), robotics (Iqbal and Riek, 2019) and various branches of mathematics and physics (e.g., Ott and Antonsen, 2017; Strogatz, 2004). Synchronization phenomena have been investigated between individuals, ranging from $N = 2$ (e.g., Noy et al., 2011, to 7–10, e.g., Alderisio et al., 2017) to $N>10$, such as in human crowds, (e.g., Gallup et al., 2012; Rio et al., 2018). Simply stated, synchronization from a physical principle requires two conditions to be met, (1) a certain behavioral proximity of the systems to be synchronized, such as a common movement amplitude or frequency, and (2) a coupling function between them, through for instance informational exchanges. Typically, metrics for synchronization built on frequency (e.g., the relation between individual and group frequencies), phase (e.g., the order parameter of the synchronization), and their stability characteristics (e.g., Pikovsky et al., 2002), allow us to capture socio-motor coordination characterized by periods of synchronization and desynchronization (Feniger-Schaal et al., 2018; Mayo and Gordon, 2020; Noy et al., 2011).

The generalization of synchronization principles to situations

[1] We ran a Google search and a PubMed search exploiting core keywords linked to emotion and acting together (for the exact terminology used for the search dated 18/05/2020 and updated 04/04/2021 please see Appendix A) and followed up on cross-references.

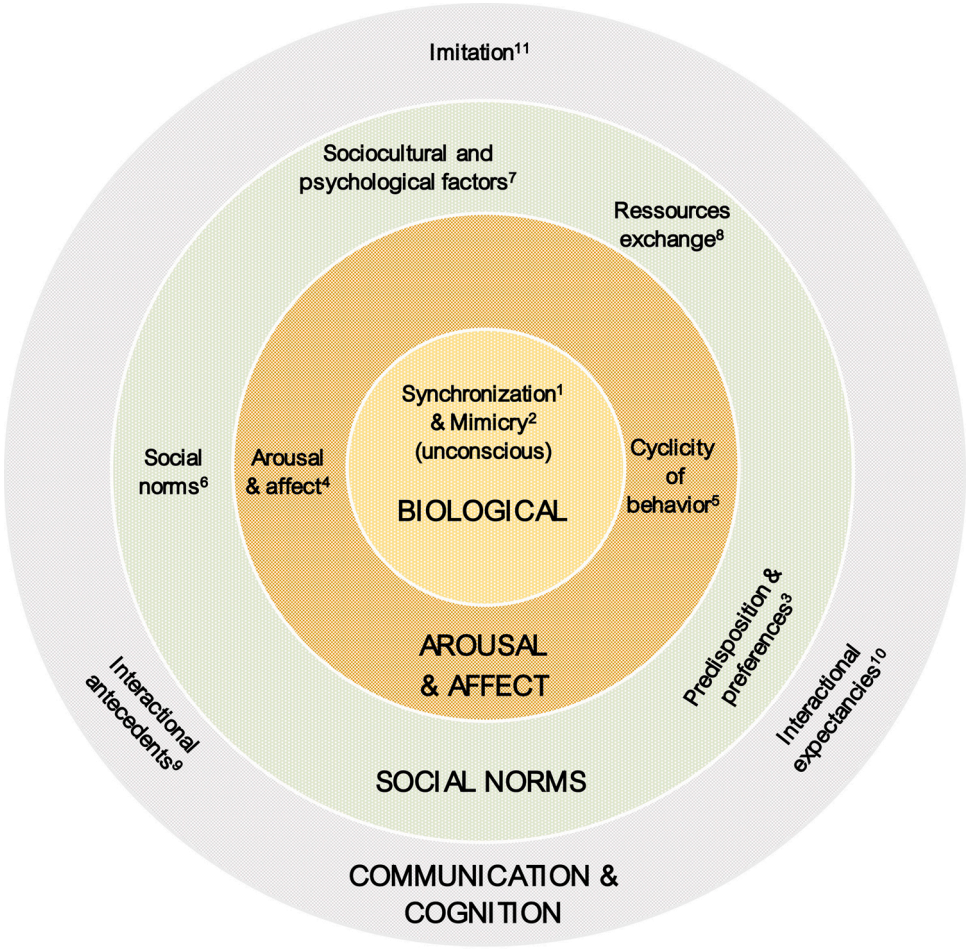


Fig. 1. Levels of joint action (after Burgoon et al., 1995); 1. (Bernieri and Rosenthal, 1991); 2. (Chartrand and Bargh, 1999); 3. (Argyle and Cook, 1976); 4. (Cappella and Greene, 1982); 5. (Altman et al., 1981); 6. (Gouldner, 1960); 7. (Giles et al., 1973); 8. (Roloff et al., 1988); 9. (Patterson, 1983); 10. (Hale and Burgoon, 1984); 11. (Bavelas et al., 1986).

involving more than two agents remains a very recent enterprise[2] . In a nutshell, models of human synchronized behaviors can be categorized in top-down estimation models and in bottom-up self-organized models. In the first category (e.g., Takagi et al., 2019), efficient synchronization between connected participants sharing a common goal is ensured by inference of the shared intention from perceived collective information and consequent adaptation of each individual motion planning. The second category concerns models proposing that synchronized motion observed at the collective level emerges from local interactions between nearby individuals. These models, such as the Kuramoto model (e.g., Strogatz, 2004) or the extended HKB model (for a review see Kelso, 2021) aim to decipher how local informational exchanges and motor adaptations contribute to that emergence. For rhythmic biological movements, coupled oscillator dynamic models have begun to explore perceptuo-motor synchronization phenomena in situations where $N>2$ (e.g., Alderisio et al., 2017; Bardy et al., 2020; Zhang et al., 2019).

It is striking to observe that a single system of differential equations (Kuramoto or extended HKB model) can capture the complexity of our interactions in perceptuo-motor tasks, including leadership properties (Alborno et al., 2015; Aucouturier and Canonne, 2017; Gnecco et al., 2013; Hilt et al., 2019; Varni et al., 2010), paving the way for the incorporation of yet missing emotional components (expressive qualities of movement). Anticipating this trend, Varni et al. (2019) recently proposed a Kuramoto-based model of entrainment in music performance of an orchestra, with two components (cf. Phillips-Silver and Keller, 2012): temporal and affective. While the first type relates to rigid temporal alignments in synchronization, the second type, initially developed in childhood during socio-motor interactions with primary carers (Barrett et al., 2007), allows for sharing emotional qualities. Thus, in musical ensembles, entrainment is seen as a temporally flexible organization between musicians, with successive periods of synchronization — stronger at the beginning and at the end of each musical phrase compared to the middle portion (Yoshida, 2002) — creating space for the unfolding of expressive performance cues.

The models of perceptuo-motor social synchronization reviewed above are only a sample of a wide state of the art across several fields of research, and additional branches, for instance social contagion models (Farkas et al., 2002; Mann et al., 2013; Ugander et al., 2012), have been omitted. However, it is striking that *none* of these models have addressed the various emotional qualities that are intrinsic to our efficient and socially relevant cooperative actions. Emotional qualities have occasionally been manipulated (Zhao et al., 2015) or measured (Zhang et al., 2016) during dyadic interaction, although not to our knowledge when $N>2$, and have not been considered in the various formalisms. In Subsection 5.2, we will propose new directions to incorporate these emotional qualities in joint action models of social synchronization.

[2] In this article, we are not reviewing experiments and models of collective motion in the animal kingdom such as bird flocks, fish schools, or fireflies' synchronized flashes, although some of them have influenced emergent models of human synchronization (see Clark, 1997; Frijda, 2007).

Table 1
Summary of distinct features of different patterns (subtypes) of socio-motor interaction extracted on the basis of literature review in Section 2.

ARCH TERM	SOCIO-MOTOR INTERACTION (AGENTS SHARING THE SAME SPACE AND TIME)			
SUBTERM	MIMICRY	JOINT ACTION		
		IMITATION	SYNCHRONY	COOPERATION
SUBCLASS	physiological, behavioural	automatic (spontaneous), intentional		interactive, divisible, antagonistic
METRICS	muscle, physiological, neural activity	body position, neural activity	phase, frequency, time in/out of sync, coupling, re-occurrence	action goals, effort, phase, trajectories, response time
SPACE RELATIONSHIP	copy		copy or not, temporal alignment pivotal	connected, but not a copy
TIME RELATIONSHIP	DELAYED		ALIGNED	
PREDICTION/ ANTICIPATION	NO		YES	
AWARENESS	LOW/ SPONTANEOUS ⟶			HIGH/ INTENTIONAL
TIMESCALES	SHORTER PHASIC ⟶			LONGER/ CHRONIC
SOCIAL CONSEQUENCES	rapport, empathy, emotion recognition	affiliation, learning, empathy, culture	affiliation, interpersonal attractiveness, cohesion	higher order, complex, longer perspective societal goals
EXAMPLES	facial expression; heart rate	body alignment	hand clapping, haka, brain to brain coupling	orchestra, line manufacturing, see-saw
EMERGENCE DURING LIFESPAN				

Note. Selected features (first column on the left) were identified as informative for understanding the subtle differences between different modes (patterns) of socio-motor interaction. Icons at the bottom depict approximations of developmental stages: babies; toddlers; preschool and school age; teens and young adults.

2.3. Neural origins of acting together

Moving together with others, as discussed in the previous section, results from the coupling between dynamical systems sharing the same space at the same time. Any stable and adaptive behavior emerges as the resultant interaction of internal dynamics and the physical and informational structure of the environment in which the dynamical systems evolve (Gibson and James, 1979; Warren, 2006). Agents learn how to act in the most efficient manner, by searching, for instance, for the most stable attractors (Thelen and Smith, 1994), or by exploiting optimal control (Todorov and Jordan, 2002). This internal self-organization of agent systems in response to external demands is fueled by previous experiences and genetic make-up (e.g., Hainsworth, 1989). Perception naturally plays a key role in delivering information to the brain about the environment and enabling us to efficiently maneuver in it. The investigations into further neural underpinnings of human joint action can be divided into two main areas of research that we herein review in turn: (i) the ability to imitate and understand movement intention in others, and (ii) the synchronization of brain activities during multi-agent scenarios.

2.3.1. Understanding movement intention in others

The cognitive ability to extract meaning from the perceived actions of others shapes how we cooperate and communicate with them (Rizzolatti and Craighero, 2004). Primates and other social animals, such as birds, are hard-wired to copy the behaviors of group mates (Heyes, 2021). Invasive brain recordings in macaque monkeys identified the neural cornerstone of this ability to visuomotor neurons in the premotor cortex V5. Commonly referred to as mirror neurons, they discharge both when a monkey observes another monkey or another human performing an action, as well as when the monkey performs the action itself (i.e., eating a peanut). Direct single cell recordings are rare in human research, but scarce evidence suggests the existence of similar neurons in the human brain. The supplementary motor area and hippocampus were identified as active during both action observation and action execution, such as reaching (Iacoboni et al., 2005). Interestingly, parts of this network were shown to be active only during observation, indicating an inhibitory role for releasing the imitation response, and other areas

discharged only during execution, suggesting a dissection of this network, referred to as the mirror neuron system (MNS) for action observation (perception) and execution (action). Here, it needs to be noted that the mirror neurons represent an undefined percentage of all neurons in the network for action observation and execution (di Pellegrino et al., 1992), and consequently the validity of using the term MNS itself can be contested; Mirror neurons contribute to, but do not dominate, complex neural networks involved in high-order understanding of action (Heyes and Catmur, 2021). There is an emerging consensus that mirror neurons play a key part only in the processing of low-level features of action for recognition and discrimination, such as body movement topography of another agent, but not of higher-level features such as intention or goal reading (Thompson et al., 2019). Ramachandran (2000) already suggested that the human leap in evolution – the creation of unique aspects of human culture such as language and arts – is endowed to the MNS, as it fosters knowledge transfer between individuals through imitation. Very recently, Heyes (2021) pointed out that imitation is shaped by development and culture, as newborns do not spontaneously imitate but learn to do so via sensori-motor learning, which promotes transformation of neurons to mirror neurons. Emotion and the reward-processing circuitry (the medial orbitofrontal cortex/-ventromedial prefrontal cortex) were shown to be linked to the observation of being imitated by another (Kühn et al., 2010), an important hint for the composition of the social glue that acting together promotes.

Some authors (Becchio et al., 2012; Centelles et al., 2011) attribute to MNS, in conjugation with the mentalizing network, the ability to distinguish individual movements from those that are socially connected, and to understand the personal relevance of the movements of others (Kourtis et al., 2010). Exaggeration or modulation of kinematics in order to convey (socially relevant) intention is often referred to as sensori-motor communication (Pezzulo et al., 2013). For example, kinematic differences in the proximal and distal parts of body movements provide pivotal information about whether someone is reaching for a cup to take a sip or to pass it on, and allow us to make adequate predictions and react accordingly before the end of the movement (Ansuini et al., 2014; Cavallo et al., 2016; Soriano et al., 2018). Regardless of the not-yet-fully-understood contribution of mirror neurons themselves in the network, the MNS acts like a bridge between first-and-third-person experiences, allowing for replay of cognitive representation, but safe-guarding the correct placement of the self (Gallese et al., 2004; Meltzoff and Decety, 2003).

2.3.2. Synchronization between brains in shared space

The moment one person interacts with another person in a shared space, we can no longer analyze those entities separately, not only in terms of motor output, but also in terms of brain activity (Balconi and Vanutelli, 2017). Eye-to-eye contact engages language production and reception areas inviting social expression and engagement (Hirsch et al., 2017). Over the last two decades, the state of the art in social neurosciences has indeed shown considerable evidence that our brain is entrained by the structure of physical interaction in the same way it is entrained by the activity of another brain when such interaction is of social nature (Hasson et al., 2012). During social interactions our brain activity is coupled with that of others (Hari and Kujala, 2009), by viewing the same content (Hasson et al., 2004; Nummenmaa et al., 2012), by movements (Basso et al., 2021; Dumas et al., 2010), and even by speech (Hasson et al., 2012; Jasmin et al., 2016). Discussed techniques, referred to as 'hyperscanning' (as more than one brain is being recorded) were specifically employed to look at dyads imitating meaningless gestures, and they identified the alpha-mu band as critical for the coordination of interpersonal dynamics, with asymmetrical patterns in brain activity reflecting the imitator-model roles (Dumas et al., 2010). In another context, two particular indexes were identified within this band in the centroparietal brain area - phi_1, phi_2; and were linked to the coordination of individualistic versus cooperative behaviors in dyads, translating into inhibition and enhancement of MNS activity (Tognoli et al., 2007). Importantly, the multi-person framework of EEG research has also started to address the niche of social affective interaction (Acquadro et al., 2016). For instance, more pronounced brain-to-brain synchrony (measured with EEG) was found in school classmates ($N>2$) sharing attention and engaging in face-to-face interactions (Dikker et al., 2017). Also, Babiloni et al. (2012) found that people with high empathic disposition in saxophone quartets ($N>2$) had higher alpha desynchronization in the BA 44/45 Broadmann's area during the observation of video recordings of their performance as a musical ensemble. We view this and other recent studies (Chabin et al., 2020; Czeszumski et al., 2020) as promising attempts to investigate the neurophysiology of embodied emotions during joint action.

2.4. Social benefits of acting together

Acting together has been shown to have profound psychosocial consequences, with evidence coming from studies looking primarily at dyads and to lesser extent, groups. The story of the interplay of emotion and synchrony starts in the most primal context of interpersonal relationships – the dyad composed of an infant and a mother. Human infants have no capacity to survive on their own and need a primary carer to regulate their physiological balance (allostasis) (Atzil and Gendron, 2017; McEwen, 2000; Van Der Veer, 1996). Emotionally receptive parents cradle their infants on the left side of their body allowing the flow of visual and auditory information to travel directly to the right hemisphere empathy circuits (Malatesta et al., 2019). Multi-modal channels of bidirectional, physiological concordance with caregivers were identified in infants as early as three months old via heartbeat rate, pupil size mimicry, vocal and affective non-verbal expression (Aktar et al., 2020; Feldman et al., 2011; Palumbo et al., 2017). Further, physiological and movement couplings were found to emerge only when the infant is unsettled, resulting in the parent reducing their own arousal to stabilize the infant (Wass et al., 2019). These first experiences of synchrony were identified to be a cornerstone for healthy emotional development (Feldman, 2012). Parental mirroring allows children to learn their own emotional responses, recognize and label them (Atzil and Gendron, 2017; Pratt et al., 2017). Motor synchrony fosters the building of first trust relationships and prosocial behaviors in human development as early as 14 months, when infants are more likely to pick up a toy dropped by a stranger who bounced with them in synchrony a moment before (Cirelli et al., 2014). Later in development, from toddlerhood to teenage years, other aspects of social cognition and self-regulation are carved by play experiences with caregivers and peers using those very foundations (Nijhof et al., 2018; Viana et al., 2020; Williams et al., 2020). Play promotes learning by imitation in the animal kingdom, through discovering how to act with others, and understanding what others feel (Feldman, 2007). This is a bedrock for empathy and social interactions in humans (Donohue et al., 2020; Viana et al., 2020; Xavier et al., 2016), and perhaps is one of the reasons why ability to synchronize movements with others continues to develop until adulthood (Su et al., 2020b).

Moving in unison thus acts as a social glue and reinforces cooperation (Hoehl et al., 2021; Wiltermuth and Heath, 2009), with a sense of affiliation between strangers (Cacioppo et al., 2014; Kragness and Cirelli, 2021) and boost in self-esteem (Lumsden et al., 2014), arising even from very simple movements such as synchronous finger tapping (Hove and Risen, 2009). The social cohesion instigated by this motor synchronization (Lakens and Stel, 2011) is part of a virtuous cycle and improves actual performance on subsequent joint action, by increasing the perceptual sensitivity of agents towards changes in the environment, those related for instance to the movements of others (Valdesolo et al., 2010).

In that way, motor synchronization seems to be a currency for our social likes and dislikes. Interpersonal attractiveness and likeability of an interaction partner is linked to the magnitude of effort in coordinating with them (in terms for instance of the relative phasing of our

body movements). When engaged in synchronization, we try harder with the person who seems happy and non-threatening (Zhao et al., 2020), or who we find attractive (Zhao et al., 2015). If an interaction partner makes a bad first impression, the chances are we will not put in our best to align our actions with them, as demonstrated by Miles et al. (2009) in a study looking at dyadic synchronous stepping. This relation is bidirectional, as moving in unison fosters interpersonal attractiveness. For instance, Cheng et al. (2020) found that during paired walking tasks a phase synchronization time ratio (how much time people walked in phase with each other) was predicted by how much they liked a stranger based on their initial impression. After a period of silent and 'chatty' walking, strangers reported increased affiliation with the person as a consequence of synchronous walking. Atherton et al. (2019) reported decrease in prejudice towards another ethnic group after physical and imagined walking.

Even if people are not 'on the move' across space, their bodies show gradual convergence towards postural alignment over the course of almost any dyadic interaction (Chartrand and Lakin, 2013; Fujiwara et al., 2019; Paxton and Dale, 2013). In human psychotherapy, which aims at aiding any shortcomings in emotional regulation in adulthood, therapists usually build a 'trust' relation (therapeutic alliance) via the above-mentioned elements of speech synchrony, as well as body movements (Bar-Kalifa et al., 2019; Lutz et al., 2020), to access implicit and explicit emotional regulation of the patient (Koole and Tschacher, 2016). For instance, head position synchrony between therapist and patient has been found to be linked to the overall therapy outcome, whereas body alignments were noted on shorter timescales to be predictive for each session outcome (Ramseyer and Tschacher, 2014) as well as experience of pain with a therapist (Goldstein et al., 2020). Weaker coordination patterns of head motion (angular displacement and velocity of the head's yaw and pitch) were also reported during conversations involving arguments between romantic partners (Hammal et al., 2014) and were proposed to be predictors of the quality of rapport with a therapist (Goldstein et al., 2020). Interestingly, people who live together, and who are hence in permanent dyadic interaction, such as roommates or couples, become alike, over time, in terms of their emotional reactivity and emotional expressions (Anderson et al., 2003). During conversations adults show convergence in use of certain speech elements such as figures and grammar (Hasson et al., 2012). Joint speech research revealed that merging ourselves with others is visible in the neural activation patterns that are different from speech production alone (Jasmin et al., 2016), putting joint speech in the realm of dynamic interplay of socially shared cognition (Cummins, 2014).

In a study on large groups ($N>5$), von Zimmermann and Richardson (2016) demonstrated that synchronous vocalization with others enhances memory performance and group effort, providing evidence for hidden wisdom of group rituals such as dancing, or singing, or when marching to fight a rival. Similarly, physiological concordance emerging between newly met group members (i.e. intervals between heart beats) explained one sixth of the variance of the performance in a drumming task in another group study (Mayo and Gordon, 2020). Both physiological and motor synchronization levels were predictive for the subjective sensation of group cohesion. Also, a study by Mønster et al. (2016) looked into the synchronization of bio-signals (heart rate and electromyography of face muscles) during cooperation (line--manufacturing of paper boats by triads). Participants were induced emotionally by the researcher acting either warmly or coldly in the interaction with the group. Exchange of smiles was linked to group cohesion (primed with the warm behavior from the experimenter), whereas synchronous increased skin conduction (interpreted as experiencing tension in a group caused by coldness in the demeanor of the experimenter) correlated negatively with measures of cohesion.

In sum, the motor and physiological coupling between humans is hardwired, and develops through childhood, to deploy group affiliation (we are members of the same tribe) and maximize collaborative efforts. Developments in dyad research have provided ample evidence for the social benefits of interpersonal alignment, with group research still being under-addressed. Therefore, the future of neuroscience of social interactions needs to include not only a second-person perspective (Schilbach et al., 2013) but also a multi-person or multi-agent perspective, and it constitutes the *raison d'être* of our review.

3. Emotions

The previous section synthesized the current state of the art in the main branches of sciences investigating how we act together, from physics-based models of synchronization to social neuroscience in humans and other animals, embodied cognition and developmental psychology. While we demonstrated that emotion is not a dominant focus to understand how people move in a group, we also mentioned some burgeoning research incorporating emotional qualities and evaluating how they affect embodied social interactions. In the current section, we reciprocate with a first analysis of current models of emotion, how they largely ignore joint action and the above models, with some recent exceptions paving the way for a more integrated approach.

3.1. What is an emotion?

Since James' attempt to answer the question "What is an *emotion?*" (James, 1884), an unresolved yet debate started on the inherently elusive nature of the phenomenon (Scherer, 2005), highlighted by Fehr and Russell's (1984) remark that "everyone knows what an emotion is, until they are asked to give a definition" (p. 464). Four decades ago, Kleinginna and Kleinginna (1981) found 92 different definitions of emotion and stressed the need for consensus. Despite substantial advancements, there is not a unified theory of emotion that would exhaustively address all the fundamental questions (Reisenzein, 2015). Interestingly, the etymology of the word "emotion" contains in itself "motion" or *emovere*, in Latin "to move", and the word "affect", more general, which relates to "producing changes" (2020[3]). Arguably, a straightforward example of emotion as a driving force of change comes from the so-called fight-or-flight response (Cannon, 1953). When scared, we prepare to run away in order to withdraw ourselves from the perceived source of danger, and when angry, we prepare to stand up and fight against the threat (Cannon, 1953; Jansen et al., 1995). Stemming from this perspective, emotional arousal holds a motivational function (Reisenzein, 2015), previously conceptualized as a mode of 'action readiness' ('Ur-affekte'; Kafka, 1950). Emotions allow us to adapt to a given set of circumstances with the aim of survival and enhancing wellbeing (maintaining allostasis), thus they entrain different action tendencies to satisfy different needs (Frijda, 2007; Frijda et al., 1989; Frijda and Parrott, 2011; Ridderinkhof, 2017), weighed up by cognitive processes against individual cost/gain and previous experience (Ferrari, 2014; Kiverstein and Miller, 2015; Padoa-Schioppa, 2011).

Classically, there were two main conceptual frameworks for studying emotion: (i) discrete models, representative of individuals emotions (e.g., anger, joy, fear, etc.), pioneered by Darwin (1872) and later developed, for instance, by Izard and Carroll (1971); and (ii) dimensional models, with a specific positioning on the coordinate system for which an emotion is an interplay between different dimensions (e.g., valence, or arousal) acting as coordinates (Plutchik, 2001; Russell, 1980) or categories linked by smooth gradients (Cowen and Keltner, 2017). Recent models (e.g., Barrett, 2017a, b) propose that emotions are emergent "constructions" of the world based on interoception (signals within milieu of the body), exteroception (signals from the environment) and previous experiences feeding in dynamic (visceromotor, motor and sensory) predictions. In this context, emotions are not

[3] (2020). *Definition of emotion* [online]. Oxford University Press. Available at: https://www.lexico.com/definition/wake (Accessed: 14 November 2020).

demarcated events, but derivative of the constant interaction between the complex dynamics of the nervous system, the body, and the surrounding environment. We experience the world factually, but it is the visceral reactions that validate the experience as 'real' (Duncan and Barrett, 2007). In a Higher-Order Theory of Emotional Consciousness proposed by LeDoux and Brown (2017), extending the high-order theory of human consciousness to emotions, the sense of self is core to emotional experiences. Although the sub-cortical circuitry, such as fear or survival circuits, are crucial for providing inputs for adaptive behavioral responses, they place emphasis on all conscious states (i.e., emotions) being instantiated in the general cortical network of cognition (cortical circuits).

Recent neuroimaging studies have shown that the emotional network is widespread in the human brain, and embraces cognitive areas (such as anterior frontal areas) beyond typical affective ones, such as amygdala, diencephalon and brainstem (Duncan and Barrett, 2007; Kiverstein and Miller, 2015) and motor readiness circuitry - premotor area (BA6) (Costa and Crini, 2011). Among other studies, Jastorff et al. (2015) found that distinct categories of emotion emerged only when looking at multi-voxel activity patterns in fMRI during discrimination of visual and dynamic emotional stimuli of different saturation. During the resting state in the MNS network, four hubs were identified as connecting points in the right hemisphere: anterior insula, right anterior cingulate, right precentral sulcus and right fusiform gyrus. Four points of connection with other structures were identified in the emotional network: right amygdala, right insula, left putamen, and left middle STS. Interestingly, Costa et al. (2014) demonstrated, using EEG recordings, that emotions from different categories overlap spatially in activation patterns with the emotional brain network, but also show distinct temporal signatures (i.e. time to peak). This aligns with Barrett (2017a, 2017b) argumentation that there are no specific pathways for emotion categories, but different neural activation can lead to the same emotion ("many-to-one") and reversely the same network can give rise to different emotions ("one-to-many") (i.e., notion of degeneracy, Edelman and Gally, 2001).

3.2. Understanding others' emotions

Despite the recent progress in emotion research, little is known about the actual dynamic link between emotion and social interaction (Butler, 2017, 2015), and the models briefly reviewed above remain largely silent about the social nature of emotion. In this section, we focus on the "shareability" of emotions, first through the prism of empathy and mechanism of mimicry, before addressing scarce evidence for the existence of group emotion.

3.2.1. Empathy

Broadly, empathy relates to understanding and 'sharing' what other people feel, need or want to do (Bloom, 2017; Ferrari, 2014), but does not infer action itself. If we refer to empathy as a parameter in prosocial behavior, we mostly mean empathetic distress — experiencing discomfort caused by perception of distress in others — which is equivalent to emotional ('hot') empathy (Bloom, 2017). However, other possibilities of sharing an affective state include cognitive ('cold') empathy (conceptually understanding what another person experiences), emotional contagion (i.e. 'catching' anxiety because we share the same physical space with someone who is anxious), and finally, compassion leading to helping behavior and altruism (Bloom, 2017; Preston and de Waal, 2002).

The well-known Perception-Action model (PAM) of empathy (Preston and de Waal, 2002) proposes that the perception of another agent's affective state activates the same neural representation of the observer (without any particular 'empathy' center), leading to activation of the same somatic and autonomic responses, an idea that was first conceived by Darwin (1872), later reinforced by Hommel (1998,1997). Research on MNS has revealed that we do internally simulate the actions we perceive (measured as shorter reaction times in consecutive execution of action performed by another agent) (Craighero et al., 1998). For example, whether we observe a facial expression of disgust, or imitate it, the same parts of the brain activate as during actual experience of disgust (Carr et al., 2003). In the same vein, observing fearful bodily expressions in others activates the motor readiness circuitry (Borgomaneri et al., 2015). Human toddlers show distress when observing others in distress (Zahn-Waxler et al., 1992), and they 'try on' emotional reactions they observe in others to see how they feel, without particular need of their own to be broadcasted (Einon and Potegal, 1994). This behavior in adults, e.g., bursting out crying when someone else does, would be considered as pathological or maladaptive, deprived of emotional containment and dissociation between self and others.

The neural underpinnings of embodied empathy, i.e., the imitation of emotional facial expressions, have so far been pinpointed to the right ventral premotor cortex (Leslie et al., 2004), with the inferior parietal lobule identified as a locus attributing a sense of agency for the self and others (Meltzoff and Decety, 2003). The brain activation of visual information containing key action features flows from the superior temporal cortex to the posterior parietal (to simulate action and code kinematics), involves frontal MNS (to identify action goal), and flows back to the superior temporal cortex to inform it about action prediction and imitation plan if needed (Carr et al., 2003). In this connectivity model the insula relays the action representation to the limbic system from the MNS and motor areas. Although simulation is a key response for understanding what others might feel, people are usually not an echo chamber for other people's feelings. The neural architecture of empathy is complex and sophisticated, endowing a multitude of social interaction scenarios, and is intertwined with cognition (Bernhardt and Singer, 2012; Ferrari, 2014). A double dissociation neurophysiological mechanism was proposed based on lesion studies for (i) cognitive (cold) empathy embedded in the ventromedial prefrontal areas, and for (ii) emotional (hot) empathy rooted in the inferior frontal gyrus (Shamay-Tsoory et al., 2009).

3.2.2. The prism of mimicry

The motor phenomenon of mimicry, or 'chameleon effect' (Chartrand and Bargh, 1999), overlapping in some ways but not to be confounded with empathy ('I felt what you feel'), relates to involuntary mirroring of expressions of our interaction partners ('I saw and show what you feel'). Mimicry, unlike imitation and synchronization, is unconscious[4], and at least partially independent of the performance ability in the latter, despite clearly being nested in the same behavioral spectrum with strong functional interconnections (Genschow et al., 2017; Rauchbauer and Grosbras, 2020). This comes with the caveat that mimicry is usually recorded in a naturalistic observation, such as matching up facial expression (rapid facial reaction) during face-to-face contact with another person (Moody et al., 2007), whereas imitation and synchronization are most often elicited and captured in less ecological scenarios (with instruction). Unintentional mimicry of body and vocal expressions unifies emotional state by means of evoking the same internal responses in agents (Hatfield et al., 2011, 1993), and is perhaps the closest to the concept of emotional contagion. Neuroimaging studies (hyperscanning mock setup for fMRI) show a similar time-locked pattern of brain activity between people subjected to watching emotional excerpts from movies (Nummenmaa et al., 2012) and listening to autobiographical stories retold by interaction partner (Smirnov et al., 2019). Adults also align their heart rate variability (Scarpa et al., 2018), pupil diameter, respiration rate, body temperature and electrodermal activity

[4] While for some scholars e.g., (Barrett et al., 2019b) mimicry is the process of an unconscious copying of other's postural, facial and other behaviors, for other authors e.g., (Centelles et al., 2011; Clarke et al., 2005; Nackaerts et al., 2012) to mimic is to intentionally imitate the behavior of the other, we us term 'mimicry' in this review in the former definition.

by their mere physical presence in one space (see Palumbo et al., 2017) for a comprehensive review on physiological synchrony). Emotional response to others via mimicry is also mediated by oxytocin hormone (Korb et al., 2016) which, in surplus, can increase mimicry of emotional expressions such as demonstrated in a double-blind study on males looking at adult and infant expressions. Similarly, Festante et al. (2020) looked into EEG after intranasal oxytocin administration and found that the enhanced alpha range of the mu rhythm desynchronization had an impact on the sensorimotor circuits involved in social perception and action understanding. Complimentary to this evidence, The Neurocognitive Model of Emotional Contagion (Prochazkova and Kret, 2017) proposed multi-modal connections between motor mimicry (facial and body, inclusive of eye synchrony) and autonomic mimicry (physiological synchrony). In this model, both mechanisms are considered separately, but operate on the social interaction interface (cognition), with MNS being an engine for shared emotional arousal and steering empathic behavior. Also, the mimicry model by Wood et al. (2016) proposes a decomposition of the perception-action loop into sensorimotor layers, encompassing functions such as moderation of emotion, prior beliefs, arousal and adaptive behavioral response. Mimicry, even on a fast timescale under 1000 ms (as demonstrated in an EMG study of facial muscles), is intermediated by the persons' own affective state and the environmental context (Hess and Fischer, 2013), as well as by affiliative goals (Rauchbauer et al., 2015). Interfering with facial mimicry (i.e., mouthguards) blocks out emotional recognition of the body and the facial expressions of fear and happiness in others (Borgomaneri et al., 2020; Rychlowska et al., 2014). This effect was reported to be mitigated by individual levels of empathy; people with higher empathy levels rely less on mimicry to recognize emotional states in others, suggesting at least a partial functional independence of empathy from mimicry (Borgomaneri et al., 2020). The social function of mimicry is also associated with longer timescales. Hogeveen et al. (2015) identified that mimicry might increase social attunement for a longer period than initial interaction via increased mu-suppression activity in MNS.

Based on the evidence above, both empathy and mimicry are key players in emotion propagation, interconnected at the functional level and bridged on the neural level by MNS. However, the dynamics of spreading motor, neural and physiological embodiment of emotions between several agents, on short and transient timescales, as well as its impact on joint action, short and long term, remains largely unexplored today. One early exception is the model proposed by Kelly and Barsade (2001), considering group emotion as resulting from individual states of the agents (shared implicitly and explicitly), captured as an affective tone that molds cohesion in the group and fluctuates. For example, adopting a group identity can inflate saliency of negative emotions, such as anger, through linking group-based appraisal to group emotion and prompting pre-designated behavioral response (Kuppens et al., 2013). One important consequence of this line of research is linked to education, as group emotions in classrooms were reported to mediate attention sharing and learning, cornerstone of long-term academic achievements (Eilam, 2019). To understand further the dynamics of 'sharing' emotion between multiple agents as they occupy or move in the same space at the same time, we give an overview of the affective embodiment research on the multi-modal signals that can carry information about emotion qualities of the agents.

3.3. The embodiment and automatic recognition of emotions

The role played by the various layers of the moving body as both receptacles and vehicles of emotional experiences has been largely addressed. Here we briefly synthesize research in psychology, neuroscience and affective computing revealing how emotional qualities emerge from multi-modal inputs (i.e., Arias et al., 2018), from face to whole body and physiology, before showing the unanswered questions at the heart of this review.

3.3.1. Face

As the most ancient and still most dominant area of emotion research concerns faces (Ekman, 1992), it is not surprising that the majority of research efforts in affective computing have been targeted to facial expressions (de Gelder, 2009). For instance, the Facial Action Coding System (FACS) was developed to provide an objective, standardized, and measurable coding system of emotional facial expressions (Ekman and Friesen, 1978). Combination of facial muscle activations (e.g., raised eyebrows, wrinkled nose, tightened lips) are differentiated as Action Units (AU) of micro expressions — i.e., instantaneous facial movements hardly perceived by the naked eye — and are subsequently identifiable as an experienced emotion (Ekman and Rosenberg, 2005). For instance, lip-corner raising is identified as an AU12 that, among others, is associated with joy. Thanks to progress in computational techniques and the increase in size of facial expression datasets, raw data rather than FACS or hybrid machine learning architectures are now used to let the mathematical models identify the relevant muscle patterns. For a detailed overview on the embodiment of emotions in facial expressions please refer to Barrett et al. (2019a, 2019b). For an overview on automatic recognition of facial expression see (Küntzler et al., 2021).

3.3.2. Whole body

A growing body of literature has shown that body expressions are at least as powerful as facial expressions in conveying affect (Atkinson et al., 2004; Hadjikhani and Thilenius, 2005; Wallbott, 1998). Studies have shown that in certain situations or for certain emotional states, the body is more informative than the face. For example, In the case of incongruence between facial and body expressions, studies (Meeren et al., 2005; Van den Stock et al., 2007) show that body posture has a strong influence on the perceived emotion. These findings were also supported by Aviezer et al. (2012). They show that evaluations made on body expressions rather than on facial expressions lead to more accurate assessment of the affective valence of the situation that triggered such expressions. De Gelder (2009) added that the body does not only convey a person's affective emotional state but also her actions and intention in response to it. Further, it should be considered that at close distance people may possibly rely on the face, but at a distance, where the facial expressions are hardly perceived, the body becomes prevalent to understand and express emotions. For an overview of bodily manifestation of emotions, please refer to Kleinsmith and Bianchi-Berthouze (2013), Melzer et al. (2019) and Witkower and Tracy (2019). Unfortunately, there is no equivalent to a FACs for the body. An initial equivalent model, called Body Action Coding system (BACS), was proposed quite recently by Huis In't Veld et al. (2014a, 2014b). They investigated covert muscle activation across various body parts in the context of anger and fear. Due to the lack of formal models from psychology and neuroscience fields, researchers in affective computing have hence turned to other fields for driving the design of automatic body expression recognition models. The four factors of the Laban Notation System (effort, shape, space, direction) (Laban and Ullmann, 1988) have provided the foundation for most of the pioneering work in this direction. A multi-layered approach inspired by Laban's Effort Theory for the automated recognition of emotion in dance performance was proposed by Camurri et al. (2003), through a computational model capturing how different dancers perform the same choreography with different emotions. Speed and energy showed to be correlated with the arousal dimension of the affective states while an extended body was generally associated with more positive states than a closed body posture. De Gelder and Poyo Solanas (2021, p. 1) defined these features as middle level features, and suggested that "*behaviorally relevant information from bodies and body expressions is coded at the levels of mid-level features in the brain*". A computational framework to model non-verbal emotions was proposed in the MEGA European project (Camurri et al., 2005) and a more recent approach was proposed in Camurri et al. (2016). By taking advantage of advanced machine learning architectures, there is today the tendency to use a more agnostic approach based on the temporal sequence of row

data (e.g., Wang et al., 2021) from movement (e.g., 3D position of each joint, angles between body segments) or muscle activity sensors (e.g., intensity of muscle activity). Still, given the limited size of the datasets and also the complexity of body expressions when embodied in everyday activity, recognition performance may gain by a combination of low- and mid-level features. By being not so directly connected to the specific high-level semantic emotions, mid-level features provide a more functional but still adaptive description of body expressions (de Gelder and Poyo Solanas, 2021) possibly enabling computational recognition systems to be able to generalize across different contextual situations.

3.3.3. Physiology

Physiological changes in relation to affect have been for long investigated. While pioneering work in the area of affective computing had initially leveraged medical devices, technical advances in the low-cost wearable sensing technology area has opened the possibility to seamlessly set up and explore ubiquitous applications (for a survey see Shu et al., 2018). Differently from facial and body expressions, physiological changes are generally used to build systems that automatically infer affective changes along the valence and arousal dimensions. This is due to the lack of clear physiological patterns associated with discrete emotions (for a review see Siegel et al., 2018). Applications for stress and anxiety levels automatic detection are possibly the most investigated areas in the computing domain (e.g., for a survey see Panicker and Gayathri 2019). General approaches in building physiological-based affect recognition models built on general statistical features (e.g., max, mean, std) extracted from the physiological responses to an emotional event. To improve performances, more specific features are extracted for each type of physiological signals. Heart-related physiological activity is possibly the most explored metrics in affective computing beyond galvanic skin conductance, as it appears related to both valence and arousal. Features related to both sympathetic and parasympathetic activities, in both time and frequency domains, have been explored (e.g., Alberdi et al., 2016), for instance the ratio between high and low frequencies. Beyond heart rate and skin conductance, respiration (Cho et al., 2019), skin temperature (e.g., Goulart et al., 2019; Wang et al., 2014), and brain signals (Alarcão and Fonseca, 2019; Torres et al., 2020) have started to gain increasing attention, demonstrating complementary performances. Similarly, research using electromyography (EMG) has shown evidence of muscle tension that is often linked to anxiety (Pluess et al., 2009). In the work by Olugbade et al. (2019), the use of EMG in concomitance with motion capture leads to clear increase in automatic pain level recognition performances in people with chronic pain. This is again thanks to a technology that is more portable and acceptable for everyday use, enabling the extraction of continuous signals, extending the possibility for measuring a large set of statistical features, and in particular features that characterize the variability of these signals (Cho et al., 2019). In a similar way to the work on non-verbal modalities, there is also the tendency to use advanced machine learning techniques that can work directly on raw data or on low-level statistical features extracted continuously over moving windows of the signals (Wang et al., 2021). However, this approach is still challenged by the limited size of the available datasets.

While each modality carries emotion information, studies have shown that multimodal recognition systems tend to lead to better performances (Al Osman and Falk, 2017; D'Mello and Kory, 2015; Poria et al., 2017). Since modalities work at different temporal scales as responses to emotional triggers, how to fuse such modalities has been, and is still, a crucial question in the affective computing community. A variety of fusion approaches have been considered. Solutions have explored low-, mid- and high-level fusions, as well as more complex architectures to fully capture the relationship between such modalities. In particular, a typical issue in multimodal modeling is that some sensors may only be available during the training phases of the model. This could be due to sensor malfunctioning or sensor availability (e.g., privacy) during deployment. Some of the explored fusion approaches have tackled such problems by learning the relationship between modalities in order to infer the missing ones when the problem occurs (e.g., Cheng et al., 2016; Rivas et al., 2021; Wagner et al., 2011). Transfer learning approaches have also been used to this purpose together with addressing the problem of limited dataset size (for a review, see Feng and Chaspari, 2020).

However, these are not the only critical questions that challenge the affective computing community. Most of the work so far has focused on mapping face, body and physiological features or their combination into emotion semantic concepts. As we move into real-world applications, such approaches are quite limited as affective experience, and its perception, are subjective processes shaped by various factors such as context (Barrett et al., 2019a) and personality (Komulainen et al., 2014). Transfer learning approaches have been used to support the development of models between for example datasets built in the lab and smaller ecological dataset, or to compensate for the limited size of such datasets (Feng and Chaspari, 2020). Other approaches have more specifically attempted to integrate the context directly in the model. For example, the use of hierarchical architectures leveraging automatic human automatic activity recognition as contextual information to body expression recognition have shown to reach better recognition performances and generalization capabilities across a variety of activities (Wang et al., 2021). Such an approach was further supported by the use of graphical algorithms that intrinsically capture body configuration information critical to both the prediction of the activity performed and the emotion expressed by the body. Similarly, Zhao et al. (2019) have explored how personality can be leveraged to improve recognition performances of personalized emotion recognition models. Using a hypergraph learning framework, they captured the relationship between individual personalities and physiological responses to stimuli, showing a clear improvement in recognition rates, and suggested that the next step would be to co-learn the personality scores of participants.

While the work above is supported by an increasing number of multimodal and also multi-factors datasets, e.g., MAHNOB−HCI (Soleymani et al., 2012); DEAP (Koelstra et al., 2012); EMOPAIN (Aung et al., 2016), ASCERTAIN (Subramanian et al., 2018), there is a real need for larger and real-life datasets that are more inclusive, and that can capture the variety of (social and activity) contexts and emotional expressions. While personality surely contributes to the experience, response and perception of emotions, there are many other personal factors (e.g., cognitive and physical impairments) that are critical to these processes. Existing datasets are still largely lacking the investigations of the above questions.

3.3.4. Multi-agent embodiment of emotion

One common characteristic of all the studies reviewed above, and of the-state of the art of embodied emotion in general, is that they all, almost exclusively, investigate the embodied manifestation of emotions in one individual in space and time (see Niedenthal, 2007). However, as said in our general introduction, humans are rarely withdrawn from natural interaction with other conspecifics. Particularly challenging is the issue put forward by leaders in emotion research (e.g., Ekman, 1992) that, arguably, the main job of emotions is to facilitate the engagement in perceived appropriate behaviors, in situational encounters with conspecifics and others. Dyadic and group situations are not only natural vectors of emotion diffusion, they are the instances where this diffusion contributes to a successful communication and enhances prosocial behaviors. For instance, Mou et al. (2016) have shown that body behavior

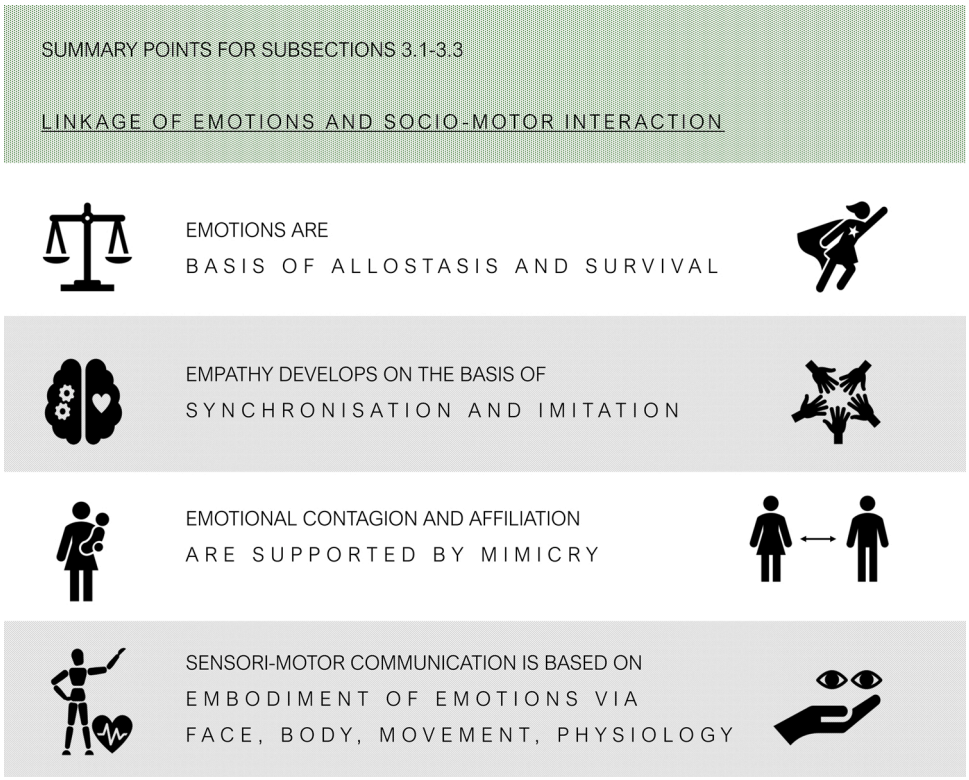


Fig. 2. Graphical summary of scientific findings reviewed in Subsections 3.1–3.3 and referred to in further sections of the manuscript.

is a better predictor of emotion-group membership than facial expression, possibly because of the mirroring that may occur in group interactions. Playing music together is one of the most significant examples of non-verbal human interactive, creative and social activities, and, as music is widely regarded as the medium of emotional expression in full body movement *par excellence*, it is not surprising to witness the first layer of research focusing on emotion transmission in embodied joint action in this domain. For example, Glowinski et al. (2013) compared the expressive movement of violinists when playing solo and in ensemble conditions, and showed that when people perform a task as part of a joint action, their behavior is not the same as it would be if they were performing the same task alone. In the same vein, Varni et al. (2010) showed, in a multi-modal interactive context of a violin duo and a string quartet, that enacting pleasure while playing enhanced movement synchrony, whereas enacting anger reduced it. In another study with a triad of musicians, body sway was structured differently with different levels of emotional expressivity during performance (Chang et al., 2019). Higher Granger coupling within the triad of musicians (piano, cello and violin) was linked to emotional expressions of happiness when compared to sadness. Finally, the quality of dance performance was found to benefit from synchronized interpersonal movements, a quality that was also enjoyed by the spectators (Vicary et al., 2017). These examples illustrate the very recent move to understand human emotion in the context of joint action. However, the full picture remains obscure as we still have little to no understanding on how emotion dynamically fluctuates and propagates in multi-agent, naturalistic scenarios (where emotion brews as a consequence of interaction between agents and environment, e.g., Dotov et al., 2021). Fig. 2 represents summary points from the Sections 3.1–3.3 showing how emotion is intertwined with acting together.

3.4. Linkage between joint action and emotion in socio-motor interaction deficits

Earlier (in Section 2.4), we presented evidence showing how moving in synchrony with others can bring positive emotions such as affiliation and attractiveness. The impact of motor behavior and its shaping role for the emotions experienced by individual agents has also been brought to the spotlight by researchers interested in mental health and wellbeing (Macpherson et al., 2020). Strong incentive for further exploration in these domains comes from clinical research investigating psychiatric conditions - neurodevelopmental ASD and severe long-term disorder of schizophrenia (SCZ), which we now shortly review.

3.4.1. Clinical evidence from ASD studies

ASD is characterized by impaired development in terms of social interaction in general, communication and motor behaviors (American Psychiatric Association), with the underlying causes being still poorly understood. The ability to share attention with others, as well as imitate them, is pivotal for human development with the first signs of sharing experiences being recorded as early as in the first year of age in typical developing children (Kellerman et al., 2020; Tomasello, 2011). Those two adaptive mental functions enable symbolic play later in toddlerhood (Baron-Cohen and Cross, 1992), which lends itself to learning how to cooperate (e.g., turn-take) and communicate with others (Nadel, 2015). Hobson and Hobson (2007) proposed that ASD come from the difficulty to differentiate oneself from others ('theory of mind'). Fulceri et al. (2018) reported that ASD children synchronize with others better and imitate them more accurately (Jiménez et al., 2014) if the spatial goal for their own movement is clearly demarcated. This helps to draw a boundary with others. The evidence for the intact ability in ASD to

imitate (Bird et al., 2007; Heyes and Catmur, 2021) is contradictory with studies reporting spectrum of difficulties with imitation and acting in synchrony (Baillin et al., 2020; Brezis et al., 2017; Fitzpatrick et al., 2017, 2016; Forbes et al., 2016; Koehne et al., 2016b; Marton-Alper et al., 2020; Tunçgenç et al., 2021; Williams et al., 2004). Impact of ASD on joint action during daily activities is also not clear from the scientific literature (Cerullo et al., 2021), with reports of children with ASD showing less interactional synchrony during naturalistic conversation with their partners (Zampella et al., 2020). Another study looking at the action of grasping a bottle, found that participants with ASD did not wait for their action partner and showed prolonged movements (Curioni et al., 2017). Trevisan et al. (2021) found that participants with ASD did not perform as well as their typically developing peers (measured as task performance and ability to sync steps with the interaction partner) in the collaborative task of carrying a table. In both reports (Curioni et al., 2017; Trevisan et al., 2021), difficulties with joint action performance were not linked to measures of other ASD-related motor deficits. In opposition to those reports, Scharoun and Bryden (2016) found no differences in healthy controls and ASD in joint dyadic tasks involving daily action (passing an empty glass of water to the researcher).

Complementary evidences exist in the brain neuroimaging literature. Studies using fMRI for action imitation and observation revealed that activity patterns for ASD in the MNS areas were altered compared to healthy control, along with networks involved in the social cognition and executive function (Chan and Han, 2020). Differences in neural activation patterns with healthy controls were also found with fNIRS during action observation and dyadic joint action in a block building task (Su et al., 2020a). Also, a recent facial electromyography study (Schulte-Rüther et al., 2017) demonstrated that although basic mirror mechanisms in ASD are preserved, they do not link to the high-order social cognition that allows emotion understanding and empathy. Difficulties reading facial expressions of negative emotions were reported for young males with ASD using EEG recordings (Van der Donck et al., 2020). Disrupted brain-to-brain coupling in ASD children was also found in the hyperscanning fNIRS study looking at joint dyadic action of ASD children with their parents during keypress tasks (Wang et al., 2020), but not in the study by Kruppa et al. (2021). Linked to this topic, we identified an fMRI study (Moriguchi et al., 2009) looking at alexithymia in adults (self-awareness of emotions), demonstrating that people with alexithymia have higher activation in the MNS area, therefore showing similar difficulties of differentiation between self and others (i.e., a neural signature in the right superior parietal structure) to those found in the ASD population. Dunsmore et al. (2019) investigated the physiological linkage between interaction partners (heart inter-beat intervals) and found that the patients suffering from ASD do not sync their heart activity with a physical presence of another person in the room as observed in healthy controls (Scarpa et al., 2018).

In sum, a prolific state of the art on ASD reveals differences at both neural and behavioral levels to neurotypical peers, in the ability to share attention during interaction with another person, to perform a joint task together, and to read and recognize their emotions. There is a contradictory evidence concerning the specific role of imitation ability in those deficits.

3.4.2. Clinical evidence from SCZ studies

Schizophrenia (SCZ) is usually diagnosed by the presence of negative symptoms, understood as social withdrawal and emotional flatness, and positive symptoms, understood as change in behavior or thoughts due to hallucinations or delusions. Green et al. (2015) reviewed the literature describing the difficulties with social interaction characteristics for SCZ and summarized them as deficits in empathy, reflective social processing - mentalizing, emotion regulation, face and voice perception. In parallel, the decrease in synchronization performances in people with SCZ compared to healthy controls was found in multiple studies, particularly for intentional synchronization (Manschreck, 1981; Varlet et al., 2012), predictive timing (Wilquin et al., 2018) and lack of sensitivity to social cues facilitating the synchronous performance with others (Cohen et al., 2017) or imitation (Sansonetti et al., 2020). In a pendulum-based synchronization task, Del-Monte et al. (2013) also showed that non-affected relatives of people with SCZ exhibit a decrease in synchronization ability, due to compromised visual tracking, pointing toward genetic SCZ phenotype for cognition. Interestingly, Raffard et al. (2018) found compromised stability of synchronization in patients with SCZ, but observed it to a lesser degree if the participants were positively primed to improve their sense of 'connectedness' to their task partners before performing the task. In a more ecologically set study by Kupper et al. (2015), participants with a paranoid type of SCZ revealed broken body synchrony patterns during dyadic role play conversation with healthy people. Synchrony negatively correlated to the social competence and severity of the negative symptoms, with participants not imitating the movements of their interlocutors, regardless of SCZ medication. Positive symptoms interacted with a lack of synchronous behavior by the healthy interlocutor, which could display affiliation, perhaps linked to the erratic movements caused by psychotic behavior.

Neurophysiological investigations of social and emotional syndromes in SCZ patients have also revealed interesting findings in the context of this review. For instance, searching for brain activation patterns in a fMRI scanner when observing recordings of finger movement and facial expressions, Horan et al. (2014) reported that people with SCZ did not differ from healthy controls, but showed a disconnection between brain activation and self-reported empathy reported through the Interpersonal Reactivity Index. In the same vein, Marosi et al. (2019) used EEG to investigate face and facial affect recognition in people with SCZ and revealed irregularities in the activity of the magnocellular pathway for face and face emotion processing. In a large study comparing MRI scans, Schilbach et al. (2016) reported differences between people with SCZ and healthy controls with regards to the connectivity in the MNS network and mentalizing network (left dorsomedial prefrontal cortex, left praecuneus, right and left temporo-parietal junction). Irregular connectivity in this area sheds light on the interpersonal difficulties that the patients with SCZ experience and on their ability to act with others. Together, these clinical studies, along with Subsections 2.3 and 3.2, mount evidence that the MNS network might be a double agent for emotion and acting together.

3.4.3. Interventions for ASD and SCZ

There is a great interest in using imitation as leverage for intervention studies for both ASD and SCZ. In an early intervention report, ASD children who received structured intervention focused on imitation and joint attention improved their social interaction skills, such as gaze following and requesting (Warreyn and Roeyers, 2014). Similarly, Landa et al. (2011) ran a randomized control study looking at the intervention targeted at imitation versus other therapy approaches long term improvement of positive affect and joint attention. Koehne et al. (2016a) reported benefits of intervention for adults with ASD using a dance therapy program focused on movement imitation and synchronization which over three months improved emotion interference along with other abilities to imitate and synchronize with others. For individuals with SCZ who participated in the therapy sessions, involving imitation of others and other theory of mind components (with a control group in a therapy focused on the problem solving skills) improved emotion recognition from the social situation and from the understanding of their intention of the movement (Mazza et al., 2010).

In sum, research in ASD and SCZ (both socio-motor interaction deficits) shows complex relationship between multi-faceted difficulties (such as differentiation from others, poor synchrony and imitation) and the ability to act together with others and understand their emotions (see Fig. 3). Neuroimaging studies pinpoint differences in information processing in those populations related to the MNS network along with its linkages to higher social cognition and mentalizing networks.

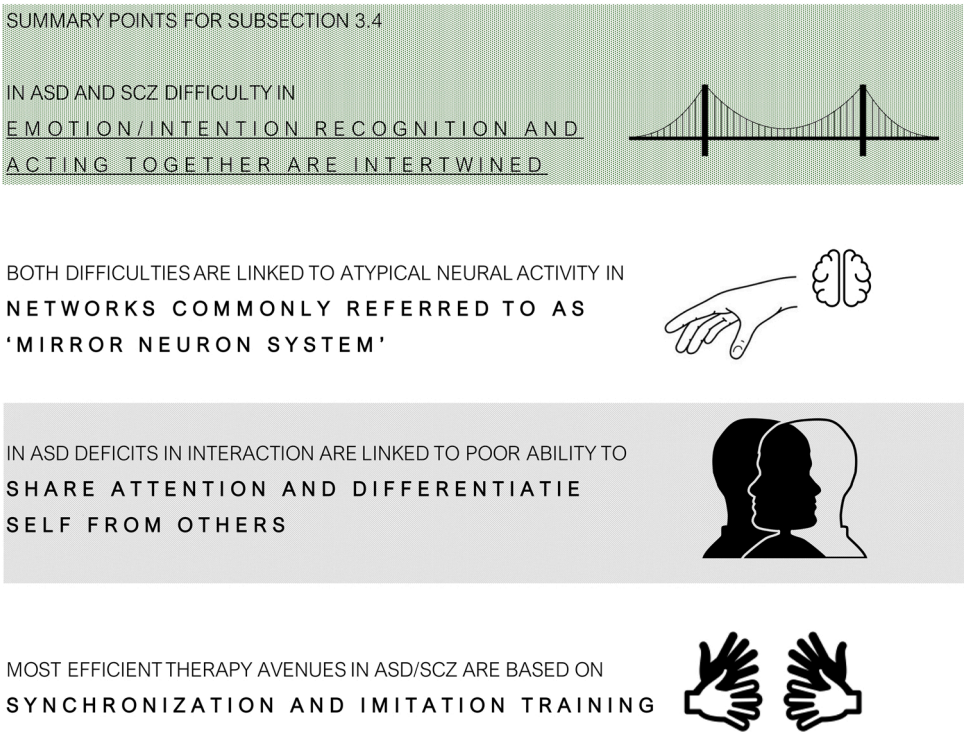


Fig. 3. Graphical summary of Subsection 3.4 highlights. *Images: Suspension Bridge by* Pechristener; *Brain, idea, mind icon from* iconfinder.com; *Grabbing Hand by Oleksandr Panasovskyi/Psychologist by Dirk-Pieter van Walsum from* the Noun Project.

4. Emoting joint action with non-human agents

Consistently over the last years, research in Human-Robot Interaction (HRI) and in Human-Computer Interaction (HCI) focused its efforts on developing social artificial agents that can initiate and maintain efficient and pleasurable interaction with a human. Emotional convergence benefits coordination between partners (Butler, 2015), and design studies in HCI have marshaled evidence that synchrony in movement qualities for facial and body expressions is essential for fluent human communication with virtual agents (Castellano et al., 2010; Marin et al., 2009; Numata et al., 2020).

Current developments in HRI are targeting real-time sensitivity to human expressions and behavior to promote long-term relationships (Castellano et al., 2008; Terada and Takeuchi, 2017). One of the main challenges is the capacity of the agent to operate on fast timescales, under one second, to be able to capture 'social moments' (Durantin et al., 2017). For instance, the *PEPPER* robot can infer possible interactive scenarios with customers via algorithms analyzing facial movement and voice signals in that time frame (Aaltonen et al., 2017). In other studies, robots adjust the interpersonal distance as a function of the estimated level of experienced emotions of the human in front of them (Bajones et al., 2017). The affect control theory offers a guiding principle used to create AI systems which are sensitive to affective states, adjusting their operations as a function of the context and need of their human interacting partners (Hoey et al., 2016). According to this theory, humans engage in situations that evoke emotions and feelings corresponding to one's culturally built affective span. In general, captured data are used to infer human affective states to which social robots adapt in various semi-autonomous ways.

Scholars in HRI have adapted and simplified the human emotional repertoire to social robots. For instance, the *ASIMO*, *JUSTIN* and *NAO* robots are programmed to express six basic emotions (and their various combinations): anger, disgust, fear, happiness, sadness, and surprise. In general, human participants correctly recognize all basic emotions from the upper-body movements with a success rate of 75 %–100 %, with some exceptions however (van de Perre et al., 2015). Other robots, such as the *iCUB* robot (Metta et al., 2008), crawl or semi-autonomously manipulate objects in various dyadic contexts, and learn by doing and imitating (Billard and Dautenhahn, 1998; Boucenna et al., 2014).

Core research activities in the field of affective interaction with artificial agents have been established around two main populations sensitive to affective interaction: people suffering from social disorders (with a particular focus on children with ASD) and elderly people. Here we briefly summarize the state of the art in these two domains, and then present recent trends in multi-agent and collaborative robotics.

4.1. Social HRI and HCI in ASD research

As it is unrealistic to expect children with ASD to continuously and smoothly interact with affectively embodied robots, adjustments have been made to simplify the child-robot interaction and discriminate between positive and negative emotions, particularly to launch social interaction (e.g., Feil-Seifer and Mataric, 2011). The *PROBO* robot, for instance, imitates animal movements which helps ASD children to recognize basic emotions (Pop et al., 2013). While some robots are only able to detect emotion displayed by humans, others, such as *QRIO*, also depict facial expressions and include corresponding body manifestations of some emotions, for instance happiness and fear, in a way that is recognizable by humans (Tanaka et al., 2004). Another example of a robot expressing emotions is *MONARCH* (Sequeira and Ferreira, 2016). This is a companion robot deployed in children's hospital facilities and successfully integrated into a rich and complex clinical environment. In the related field of HCI, social robots are often replaced by virtual agents designed to create a specific social relationship with their human counterparts. Virtual and augmented realities are commonly used to help ASD children to focus on and recognize facial nonverbal cues (Chen et al., 2016), to learn to recognize and express emotions with their full-body movement (Alborno et al., 2016), to learn the required social skills (Lorenzo et al., 2019) or to promote verbal and nonverbal communication skills via joint actions (Srinivasan et al., 2016, 2015).

4.2. Social robotics for the elderly

The ageing population is another major category targeted by research on HRI, at home (e.g., Fischinger et al. (2016)) or in nursing institutions (Moyle et al., 2013). Older people develop a wide variety of age-related conditions that can cause their vulnerability to minor stressor events and lead to loss of autonomy: this phenomenon is commonly known as "frailty". A number of interventions have been developed to target negative symptoms such as loneliness, anxiety and depression, which can also accompany dementia (Cifuentes et al., 2020; Kachouie et al., 2014; Valentí Soler et al., 2015). One example is a NAO robot-based rehabilitation program for people with dementia based in a geriatric ward, which reported higher outcome scores than conventional therapy on the immediate well-being and satisfaction (Rouaix et al., 2017). Similarly, *PARO* is a robotic seal that elderly residents in nursing homes benefit from by verbally interacting with it (Moyle et al., 2013). *HOBBIT* is another emotional assistive caregiving robot used at home to prevent falling (Fischinger et al., 2016). Further, a Social Assistive Robot exercise system was reported as more engaging the elderly in aerobic physical activity than virtual coach (Fasola and Mataric, 2012). The robot in Zhang et al. (2019) computes continuously the person's movement trajectory, while assisting with their dressing, but is not emotion aware. These are only five examples that have been extracted from a plethora of research and proof-of-concept studies and have demonstrated how useful HRI and HCI approaches can be in the clinical context, as well as at home, to accompany healthy aging.

4.3. Environments of multiple human and artificial agents

When it comes to the environment being social, i.e., acting together in a group, a modest number of studies overcome the limitation of a robot(s) of working with more than one human, and only very few robots are adapted to such interactions. For example, the interactive robot *KEEPON* can engage in both dyadic and triadic interaction due to emotional expressivity which aids to build joint attention with the interaction partner, e.g., looking in the same direction as the human (Kozima et al., 2005). Besides *NAO,* which is known to be able to work as a guide in a museum for a group of visitors (Gehle et al., 2014) or with school-aged children (Hood et al., 2015; Ros et al., 2014), and *TIRO* which serves as a teaching assistant in musical classes (Han et al., 2009), the literature on human-robot group interaction remains scarce and almost exclusively in the form of "one-to-many" (a *star* graph as in the guide situation) in contrast to a more generic form of "many-to-many" (a *complete* graph, see Bardy et al., 2020). One of the unique endeavors employed triads of BEAM robots in a semi-autonomous control mode (Wizard of Oz) during game playing scenarios with human triads (Fraune et al., 2019). Human participants reported changes in subjective fear and motivation moderated by the perceived cohesion of the robot group, in comparison to other typologies with one human versus three robots and vice versa, and one-to-one interaction between a human and a robot. This indicates a breadth of emotional component to be explored in intergroup dynamics between human and artificial multiple agents, despite robots not being embodied with sensori-motor communication abilities (embodiment of emotion). However, despite being 'emotionally neutral', in a study by Kochigami et al. (2018), robots NAO and PEPPER played social roles by creating social ties between human group members (children and adults), and successfully facilitated interaction between them. Examples of similar studies are limited in number (see Fig. 4). Sebo et al. (2020) pinpointed key messages emerging from the current state of the art: (i) behavior in one person to one robot does not interpolate on the group behavior; (ii) verbal and non-verbal robot behavior shapes the response within the group and can support cohesion; (iii) people are more likely to engage with a robot when they are in groups; (iv) similarity (anthropomorphism) to humans plays a role in the

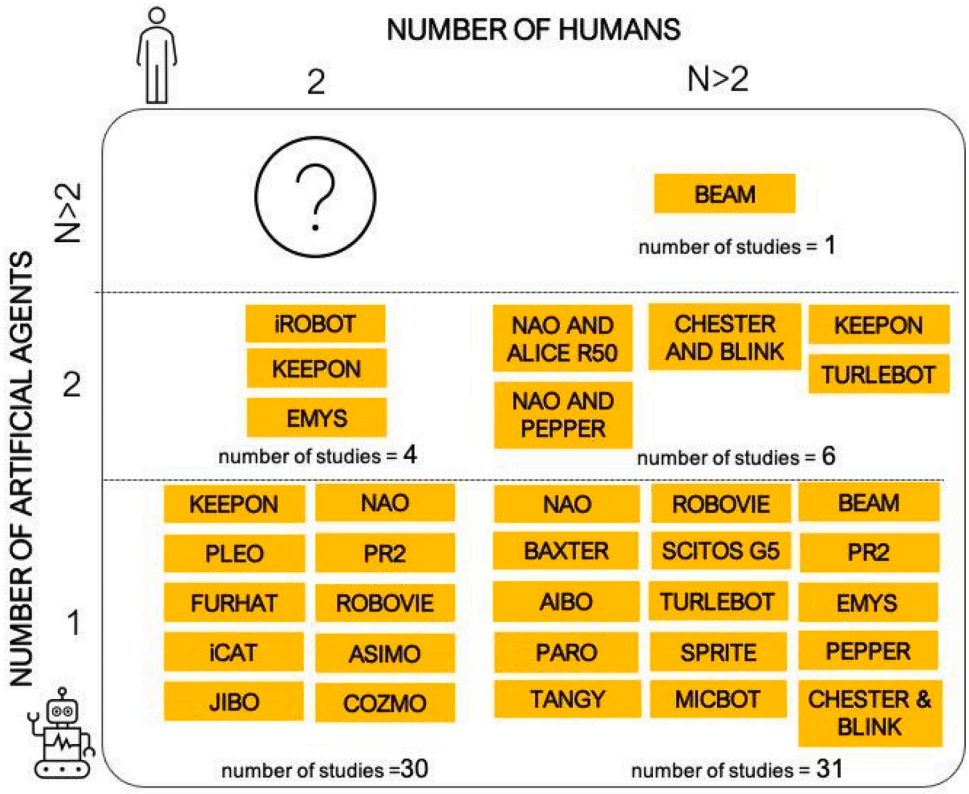


Fig. 4. The 2D matrix of the number of agents (persons ≥ 2 and robots) in HRI interaction extracted from the literature review of Sebo et al. (2020). Examples of the names of the robots used are placed on orange tiles with the count of overall studies identified by the researchers (refer to Table 1 in Sebo et al. (2020) for further details).

integration of robots in a group. The dynamics of how emotion can be shared or propagated through the heterogeneous networks of several humans interacting with several artificial agents is unknown and has profound implications for the future of collaborative robotics.

4.4. Collaborative robotics in the industry

Emotion sharing as a means to facilitate social interactions in HRI has so far mostly been applied in therapeutic settings (see Subsections 4.1-4.2). In industrial settings, however, despite the heavy reliance on industrial robots for manufacturing, such examples are still rare. It is believed though that an essential component of the next industrial revolution, often referred to as Industry 5.0, will be that of the collaborative robot, a robot that can complement human co-workers, performing tasks that are either tedious or dangerous (Demir et al., 2019). The reason is because industrial sectors still lacking in terms of automation are those that cannot be fully automated, as they require human participation (Elprama et al., 2016). It has been recognized, however, that introducing collaborative robots to workplaces might have an adverse effect on social interactions in these workplaces. Untrained personnel, in particular, tend to expect the same social signals from robots as they would from human colleagues and expect the robots to adhere to existing social practices (Fischer, 2019). If collaborative robots fail to understand social signals and respond accordingly, they will be seen as impolite, cold and uncooperative. It also represents a missed opportunity to convey the robot's capabilities, while making communication more dependent on disruptive explicit signals, when more fluent implicit signals would have been preferable for seamless collaboration (Breazeal et al., 2005). Fischer (2019) further argues that collaborative robots do not only need to understand and produce social signals but that these signals need to include emotional expression. The reason, as seen in the above sections, is because sensori-motor communication of emotion and intention is an integral part of conventional social practice. A robot is simply expected to be sad when delivering bad news or happy when successfully completing a challenging task. Emotional expression may also be used to communicate real needs, such as when the system is running out of power and needs to be recharged. Recognition of human emotional expression under natural industrial conditions is difficult, as the technology needs to be both non-intrusive and robust over time. Speech (Khalil et al., 2019), gaze (Admoni and Scassellati, 2017) and facial expressions (Li and Deng, 2020) become more convenient cues than gestures or full body movement (Liu and Wang, 2018). However, with the introduction of cheaper wearable sensors, emotion recognition from EEG has recently become a viable alternative (Toichoa Eyam, 2019; Zheng et al., 2019). For expression of emotions, collaborative robots are limited by their embodiment and interfaces have more often been used for conveying information than for social signaling. Most collaborative robots only rely on projections of faces on flat screens to express emotions (Kalegina et al., 2018), if such expressions are used at all. There are recent examples, however, where the embodiment has in fact been exploited for social signaling, even highlighting the importance of a breathing motion (Maric et al., 2020; Terzioglu et al., 2020), opening new emotion-based perspectives in collaborative robotics.

5. Avenues for future research

Sections 1–4 presented ample evidence for the interplay between emotions and joint action. Humans are unequivocally attuned to each other, with body movement being a powerful carrier of idiosyncratic information (Cutting and Kozlowski, 1977; Loula et al., 2005; Troje, 2002) and socially meaningful qualities (e.g., Centelles et al., 2011; Clarke et al., 2005; de Gelder and Poyo Solanas, 2021; Nackaerts et al., 2012). Information about the arousal of a person encoded in movement and their intention can be transferred to another person, for example, as a forewarning of a threat. Being able to detect those non-verbal signals from others, along with the ability of humans to couple their body and brain activity, is the cornerstone of successful communication and cooperation between people. We strongly believe that interaction is key to understanding the human brain, as the human brain, through interaction with the environment, is of a physical, but also fundamentally of a social nature (Section 4 recaps why this also applies to hybrid interactions between humans and artificial agents). We acknowledge, as do other researchers, that social interaction should be at the forefront of neuroscience research (Schilbach et al., 2013). Some recent attempts, such as the social alignment theory, using herding modeling by Shamay-Tsoory et al. (2019), are providing other important milestones towards this venture.

In this last Section (5) of our review, we put forward the idea that emotional arousal should be considered as an integral part of the so-called 'motor system', shaping and fine-tuning the real-time socio-motor interaction with others. Emotions arise as responses to the stimuli in the environment (with a function to maintain/restore allostasis) and bear subsequent impact on one's perception, affective state, ongoing and future movements (e.g., Wood et al., 2016). Thus, we propose to incorporate emotion in a joint action context as one entity, a 'third eye' that steers other mental and physiological processes to navigate the rich, multi-modal layers of the multi-agent social space. As emphasized before, the scientific evidence on the emotional embodiment during socio-motor interaction is limited (see Section 3.3 for overview), especially in terms of studies exploring real, not enacted, emotional arousal with naturalistic scenarios as a backdrop. To disentangle and decode the emotion propagation and socio-motor interaction not only via movement, but also via physiological processes, we propose to follow new research avenues (Subsections 5.1–5.5) to decipher the unknowns about interplay of emotion and joint action (see below the research questions we have identified as a part of literature review process, continued further on Fig. 6).

Research questions

We now know that some features of body posture and movement carry emotional qualities (de Gelder and Poyo Solanas, 2021), but can we find a motor signature of emotional arousal and valence in body movements in the context of socio-motor interaction (regardless of particular body parts) specific to i.e., particular levels of valence or arousal? To what extent context and culture shapes this signature during joint action? Is there a group emotional signature emerging from individuals sharing space at the same time (i.e., euphoria of football fans in the tribunes) (Subsection 5.1)? How do emotions evolve and propagate through the network of agents (humans or hybrid groups of human and artificial agents) and if so, how do they influence the outcome of joint performance (Subsection 5.2)? Further, we dive into the need for adoption of multiple timescales approaches, which emerged throughout this review (Subsections 2.4, 3.2–3.4, 4), showing that environmental function of emotion unfolds over multiple time windows, throughout physiological and movement qualities, as well as that some factors in socio-motor interaction are only meaningful when looked through an appropriate temporal lens (i.e., expertise, culture, previous experience with an agent). What are then the crucial timescales we need to integrate into the research agenda to advance this enquiry (Subsection 5.3)? How can AI techniques assist in this process, and unravel the patterns of information about emotion/intentional qualities and its propagation in agents during joint action (Subsection 5.4)? Finally, we dive into the world of digital, currently disembodied interaction, and highlight the notions that recent pandemic experience has left in terms of interplay of physical presence and emotion embodiment during social interactions (Subsection 5.5).

5.1. The notion of emotional motor signature in joint action

A large body of the work reviewed in Section 3.3 cements the foundations of the embodied nature of emotions, according to which expressions of emotional dimensions, rooted into common neurophysiological structures between cognition and action, are diffusing into movement physiology and are visible in facial, distal, as well as proximal parts of the body (Barrett et al., 2019b; de Gelder and Poyo Solanas, 2021; Kleinsmith and Bianchi-Berthouze, 2013; Melzer et al., 2019; Witkower and Tracy, 2019). Interestingly, this extensive literature does not yet intersect with another parallel body of research developing concepts and methods to assess Individual Motor Signatures (IMS), the idiosyncratic way each individual moves (e.g., Słowiński et al., 2016). The pioneering work of Johansson (1973) showing that - transformational invariants (Malcolm, 1953) persistence in some dimensions (e.g., length, ratios) across the motion of others (e.g., global transformation of the local optic flow) could help observers to quickly extract person-related properties, is very relevant to the socio-motor interaction context. IMS often relies on movement velocity as a key feature, as it is both stable across time and repetitions for each individual (movement similarity) and differential between individuals (inter-individual movement difference). Differences in the way people move during the performance of a motor task can be captured by using 95 % confidence interval ellipses in the similarity space (Słowiński et al., 2016). This is an abstract two-dimensional geometrical space minimizing distances between repetitions and individuals by using ad-hoc dimensional reduction techniques. Ellipses can be large or small depending on intra-individual variability and can be close or distant from each other depending on between-individual variability. The approach has proven useful in identifying IMS in various populations, ranging from healthy individuals to people suffering from schizophrenia (e.g., Słowiński et al., 2017). It has also proven useful in various tasks and contexts such as in the mirror game (Słowiński et al., 2016) or during improvisation movement (e.g., Coste et al., 2019), and at different distal or proximal (and more postural) parts of the body (e.g., Coste et al., 2021). Whether IMS, {as well as Group Motion Signatures (GMS, inter-group movement differences), i.e., the way IMS are assembled together in an ensemble of individuals engaged in reaching a common goal during joint action}, are emotionally neutral, and whether they are of different shapes and locations in the similarity space when produced in various emotional contexts (intra-subject variability) remains open to investigation (see Lozano-Goupil et al., 2021, for a first evaluation of Emotional IMS). Taking this road would not only answer the above questions, but would also offer a way to reconcile existing theories of emotion and those of embodied social interaction, inclusive of intra- and inter-individual/group variability and concepts such as motor accents (e.g., Ting et al., 2015), in a real-life context of a joint action.

5.2. Emotional group synchronization models

As emphasized in Section 2.2, models of perceptuo-motor social synchronization when $N>2$ have not yet incorporated emotional qualities in their constituents, i.e., they remain emotionally neutral, despite the evidence gathered in this review that emotions are contagious, propagate through the social network, and constitute the essence of joint action. One urgent avenue of research requires a complementary approach incorporating emotional qualities in experimental and modeling scenarios. On the experimental side, the manipulation of positive, negative, and mixed emotional qualities, be they enacted or (ideally) induced, and the observation of how these qualities propagate from one node to the next across the collective sensori-motor network, converge or conflict, is requested. On the modeling side, coloring coupled oscillator models of synchronization with those emotional qualities would help to better understand, and generalize, the underlying propagation mechanisms. For instance, the network of coupled Kuramoto oscillators presented in Section 2.2, capturing group synchronization regimes when perception is present (see Bardy et al., 2020, for details), needs to be adapted to incorporate emotional qualities at individual levels, such as:

$$\dot{\theta}_l(t) = \omega_i + c\sum_{i-1}^{N} a_{ij}\sin\left(\theta_{jEM}(t) - \theta_{iEM}(t)\right)$$

Where N is the number of agents, θ_{iEM} the phase of the movement of the i-th agent under emotion EM, ω_i their natural frequency, and c the strength of the coupling with the other agents when perceptual coupling is established. Coefficients a_{ij} are set to a value between 0 and 1, depending on the dyadic perceptual coupling between agents i and j, i.e., the spatial configuration of the group. Coloring such oscillatory models with emotion-aware individual signatures (see Fig. 5, Example C), nourished by experimental data, would therefore be an operational way to close the gap between Sections 2–3 of the present review.

5.3. Embodied emotion across multiple timescales

In this review, we have hinted at the concept of multiple timescales on a handful of occasions. In Greek pre-Socratic philosophy time was represented by two notions; Chronos, sequential and linear time as we currently understand and apply it in a metric system (chronological time), and Kairos; which resembled the 'right' time, especially in the context of an action affordance (i.e., time for harvest). A myriad of research studies has provided data-driven rationale in favor of the use of multiple timescales to capture animal behavior and physiological processes (be it signal duration, temporal resolution, units applied or temporal dynamics). The evidence for multi-timescale behavioral organization has been recently investigated in *C. elegans*; showing how neural dynamics in this much simpler organism (slow - low frequency; fast - high frequency) orchestrates different movements and allows for flexibility of behavior (Kaplan et al., 2019). In humans, communication is regarded as a robust example of multi-modal behavior stretching across multiple levels of temporal structures due to the variety of interconnections between internal systems such as respiration and movement (Bardy et al., 2015; Pouw et al., 2021).

5.3.1. What do we know about temporal aspects of emotions?

Since the works of Solomon and Corbit (1974) it has been widely accepted that emotions unfold their dynamic over time, rather than spike events, with complex temporal structure (De Gelder et al., 2004; Frijda, 2007). Regardless if the stimulus is aversive or hedonic, the response curve for high arousal physiological reactions (i.e., heartbeat) unfurls as (i) rise to peak, (ii) adaptation period, (iii) recovery with reversed peak to re-establish baseline within 30−60 s. In a LORETA EEG paradigm, Costa et al. (2014) found a precise pattern of neural signatures of fear, disgust, happiness and sadness, with differences emerging mostly in the temporal characteristics of neural activation, but not the spatial spread. The differences that emerged are as follows: (i) Early onset (around 200 ms post exposure) and shorter duration characterized emotions - fear and disgust, which are associated with a need for quick body reaction; – (ii) Early onset (around 260 ms post stimuli) with a second processing peak at around 400 ms in different areas - happiness; and (iii) Late onset (around 400 ms post exposure) and longest duration (90 ms) – sadness. Personal diary study (Verduyn et al., 2015) reported similar temporal patterns linking to the adaptive behavior evoked by emotion, meaning that fear and disgust operate on fast timescales as they require quick fight-or-flight reaction; whereas emotions like anger

or joy, on average, take longer to disperse through action (Costa and Crini, 2011; De Gelder et al., 2004; Feldman Barrett and Finlay, 2018; Frijda, 2007). Notably, sadness was earmarked as the longest in duration, perhaps because its presumed function is to pave a pathway to rumination, motivation for change in personal circumstances or acceptance. Personal dispositions, from reactiveness and resilience on a physiological level to higher cognitive functions such as emotion regulation processes (reappraisal), were highlighted as subjected to inter-subject differences (Solomon and Corbit, 1974)

5.3.2. How emotions influence motor timing?

Distal movements in particular (i.e., object manipulation) are a clear *reservoir* of emotions, a cornerstone assumption of forensic criminology. Gao et al. (2012) analyzed movement in a touch-based game and found (i) the length of the stroke to be indicative of the dimensional quality of valence, (ii) speed and direction to be indicative of arousal, while (iii) pressure specifically discriminated anger from other states (where increase in energy transmitted to movement has functional significance). Similarly, more frequent manipulation of the computer mouse was found to be associated with higher stress (Hernandez et al., 2014). During paced synchronization, adults and children tapped faster if they were primed with negatively valenced pictorial stimuli before the trial (Monier and Droit-Volet, 2018). The speeding up of motor response was interpreted as activation of the fear circuitry evoked by negative emotional induction (LeDoux, 2014), leading to the speeding up of the internal clock system (Cheng et al., 2016) and shifting movement towards faster timescales. Further, emotional arousal leads to subjective perception of time in some tasks (Gil and Droit-Volet, 2012), making a point that time perception is tied to the quality of stimuli (Grisey, 1987). This becomes particularly relevant in the context of untangling the dynamics of joint action and emotion (i.e., during synchronization).

5.3.3. What do we know about group temporal dynamics?

Vesper et al. (2011) has demonstrated that better coordination is achieved in dyadic action when participants make themselves more predictable (less temporally variable), in comparison to performing identical (pointing) movement alone or next to another person without intention to act together. Grammer et al. (1998) demonstrated that opposite sex pairs show a complex temporal structure of interaction patterns of body movement during conversation, which is repeated if both sides show interest, and is unique for each dyad. In a previously mentioned model of a psychotherapeutic alliance (Koole and Tschacher, 2016) three timescales were proposed for interpersonal synchrony, namely; (i) a *phasic* time-scale, which runs from a few hundred milliseconds to 10 s, characteristic of motor synchrony, (ii) a *tonic* time-scale, which runs from about 10 s to an hour, and involves more complex forms of social cognition, such as language and reasoning, and (iii) a *chronic* time-scale, stretching from weeks to years, and which involves the development of complex emotion-regulatory abilities. Bardy et al. (2020) reported that social memory (expertise in dance practice, related to (iii)) can affect the ability to synchronize with others under different perceptual strains. Similarly, experts in capoeira and tango had higher ability (kinesthetic ability) to imitate and synchronize with others, in comparison to athletes who also practice group sports, but without the synchronization component (Koehne et al., 2016c). More broadly, Burgoon et al. (1995) suggested that behavioral norms can pass from one generation to another as culture (i.e., think of the jovial behavior expected from a salesman versus the stoicism of a medical professional). An unexplored territory is investigation of previous personal experience with agents partaking in socio-motor interaction, which can trigger certain emotions prior or during the execution, due to predictions of the internal model (Barrett, 2017b).

Taken together, these findings hint at a hidden hierarchy of socio-motor interaction, from low-level, fast timescales, which are more appropriate for immediate behavioral synchronization and responses, to high-level, slower timescales, which involve complex cognition and emotion regulation, linked to perception of emotional qualities and social memory. In this context, future research should apply a multi- (or inter-) modal multiple timescale approach for studies set on the interface of emotion and human joint action.

5.4. Leveraging artificial intelligence (AI) methods to capture emotions in socio-motor interactions

AI offers powerful analytical tools to deal with complex data, and so it is a valuable method for investigating individual and group motion signatures of emotions within the context of joint action. As discussed in Section 5.3, a multiple timescale approach is required to build a solid foundation of how various emotional qualities propagate in joint action could provide a window into relative aspects of time and how it is linked to the differentiation of emotional qualities in movement and the opportunity to act collectively. However, AI methods that address multiple timescales are largely limited to encoding each temporal variable (e.g., each different modality or modality dimension) separately. Such methods can only really create models tuned to a single timescale per temporal variable. Perhaps the more promising direction is methods that capture multiple timescales within each variable itself.

The few studies in this direction (e.g., Gurcan and Nguyen, 2019; Ma et al., 2019; Yamashita and Tani, 2008; Yang et al., 2020) have so far been constrained to individual action modeling. Two of the few exceptions are the multiple timescale recurrent neural network (MTRNN) (Yamashita and Tani, 2008) and the Approach Group Graph Convolutional Neural Network (AG-GCN) (Yang et al., 2020). Whereas the AG-GCN was designed to model group behavior, the MTRNN was originally developed for individual action scenario but has been extended to dyadic (Hinoshita et al., 2009a) and group interaction (Jaderberg et al., 2019), although only for robots in simple robot-robot interactions and bots in a multiplayer computer game. There is not much analysis of the behavior of the MTRNN in the multi-agent settings, but a functional hierarchical structuring of events in the movement sequences sampled was shown to emerge through modeling at multiple timescales in its original use (Yamashita and Tani, 2008). Similar findings reported for multiple timescale AI architectures explored in the context of natural language processing (Chung et al., 2017) underline the value in pursuing multiple timescale modeling for further understanding emotion in joint action. Moving forward, there is the need for new architectures that simultaneously: 1) have pathways for both action and emotion recognition, drawing from neuroscientific findings of multitask coding of observed action (behavior identification and semantic interpretation) in humans (Gallese, 2007; Iacoboni et al., 2005); 2) with multiple timescales processing for the two, rather than for one or the other (such as in Hinoshita et al., 2009b); and 3) capture individual as well as group signatures in group settings. Such architectures have the potential to maximize the value of AI for different aspects of emotion expression, perception, and propagation in the context of joint action.

In the current age of deep learning where low-level layers are entrusted with the extraction of signatures (i.e., features) from continuous streams of sensor data, there is a shift away from focus on hand crafting of computational features, with increasing significance

instead placed on the design of architectures that learn relevant features organically and directly from sensor data. A more valuable approach may be a blend of both methods. On one hand, automatic feature extraction sub-architectures could perhaps lead to (deeper) insight into what behaviors or other responses at individual and group levels characterize emotions in joint action. Contemporary understanding of these individual and group signatures could, on the other hand, be further explored by employing them in the form of hand-crafted features. The large number of existing studies on affect recognition (see Section 3.3 for a discussion of some of these) would be valuable in guiding the choice of individual level features to examine in the context of joint action. The minimal set of studies (Mou et al., 2015; Ukita et al., 2016; Yang et al., 2020; Yücel et al., 2013), that have used group relations features for affect recognition and related AI areas highlight differences in distance, speed, and direction (as well as displacement and/or velocity) between the individuals in a group as additional features to consider. As anticipated by some studies (e.g., Ukita et al., 2016; Yücel et al., 2013) the problem of determining (the extent of) a group of interest is a challenge that may need to first be addressed, especially for autonomous AI to be integrated into real world settings, before understanding how emotion experience in joint action can be possible (for an overview of the current state of the art on emotion recognition on groups please see Veltmeijer et al., 2021). Such an AI system would need to be able to determine if there is any joint action group present in a given location or sequence of events, the number of such groups, and the membership of each of them.

5.5. *Emoted disembodied joint action in the digital world*

The COVID-19 pandemic has speeded up our move into digital encounters across all aspects of our social life, be it work, education, leisure or even health. *V*irtual interactions have enabled millions of people to continue working together remotely (video calls e.g., Zoom or virtual spaces with people represented by avatars e.g., *Sococo* or *Virbela*). However, these virtual interactions have been impoverished in emotional context due to the lack of information, coming from gestures, body postures and facial expressions, about emotional arousal and agent's intentions. These non-verbal cues are critical to communication, understanding and bonding, recently captured by de Gelder and Poyo Solanas (2021) as mid-level qualities. Musicians, teachers and athletes across the globe have experienced how different it feels to perform without an audience feeding back their reception. After all, part of our identity comes from socio-motor interaction with others, by which we can express our personal qualities, such as being funny or having a preference to lead or to follow. Others reflect our qualities via sensorimotor communication, which is the foundation for validation and updating our sense of self. The lack of such easily accessible non-verbal cues in virtual spaces and the amplification of facial and gaze cues over body cues in video calls (e.g., *Zoom*) have been suggested to contribute to "*Zoom* fatigue" (Bailenson, 2021). In sum, lack of socio-motor interaction with others deprives our brain from the habitual process of predicting the unfolding of their actions in order to efficiently affiliate and cooperate with them in real time. Given that a digital environment will most probably last to a certain extent post COVID-19, it opens the opportunity, but also calls for embedding and facilitating joint emotional interaction to become effective. How to enhance the communication of emotional expressions in virtual spaces has been previously investigated. However, these studies have been limited to simply manually expressing such states (e.g., Pita and Pedro, 2011) showing that in such situations people spend more time in carefully crafting verbal affective expressions than they do in gestural ones, possibly because of the lack of embodiment of the latter. Sensing technology, affective computing and sensory interactions or substitution research can have a crucial role in creating and sharing a sense of agency, a felt embodied affective state and at the same time advancing our understanding of how emotions become joint experiences. Leithinger et al. (2014) have shown how our own hand gestures can be transferred to another physical space as 3D objects for the others to experience in action. Remote tactile interactions, through the use of wearable devices that stimulate the other person skin in response to a remote tactile gesture (e.g., tactile exchanges in Huisman et al., 2013), such as skin stretching or being pinched (Hamdan et al., 2019; Muthukumarana et al., 2020), could help maintain the affective power of our non-verbal behavior during remote communication. Unfortunately, none of these studies have yet explored how such approaches are suitable to transfer the emotion qualities of an action and definitely not how such emotion qualities transfer across a group. Instead, transfer and group dynamics have been explored through disembodied representations of emotion-related signals (e.g., galvanic skin response or HRV) or inferred emotions through computational algorithms (Ardizzi et al., 2020; Gashi et al., 2019). Also, very little attention has been given to the spatial and temporal aspects which characterize joint emotional experiences, which are becoming even more critical than before. Studies have also shown that the perception of self-location can be altered through the right manipulation of sensory feedback, as in Lenggenhager et al. (2007). As Nadler (2020) highlights, space takes new meaning and creates new affordances in these virtual spaces that alter the meaning of joint interaction. From a computational perspective, modeling group emotion may require us to integrate in the computational models the dynamic characteristics of such virtual spaces that are affected by their properties and typology of information flow (Bardy et al., 2020).

6. Summary

Emotions move us across multiple levels of qualities and timescales, for our own survival, and for higher collective purposes. The sheer physical presence of others in shared space and time fulfills the most primal of human needs, which is to belong to a group. The recent pandemic experience (COVID-19) has demonstrated a devastating effect of disruption of routine social interactions. Joint actions have been obstructed by social distancing measures or by being moved entirely to the digital world. Confinement has had profound and not yet fully understood effects on mental wellbeing across all age and gender groups, (Ammar et al., 2020), and has had impact on the development of social skills in children deprived of contact with their peers (Giménez-Dasí et al., 2020). In this review we have highlighted a need to close the gap in the research between emotion and socio-motor interaction across different disciplines, and have prompted specific questions to the scientific community to do so. Although various branches of science have separately focused on joint action and on emotion, there is a growing necessity to understand how emotions flow across our embodied social interactions, and how they affect us as individuals, as a group and as a society.

Fig. 5 depicts dimensions that were identified in this review as meaningful to obtain a full picture of emoted socio-motor interaction, inspired by the research "landscape" of second-person neuroscience, proposed by (Schilbach et al., 2013). Sections 2–3 are represented in the lateral panel as emotion depicted a shade gradient of agents engaged in interaction (where color denotes interaction type), and organized the possible consequences of socio-motor interaction, into three 'working' categories that emerged during our literature search: performance,

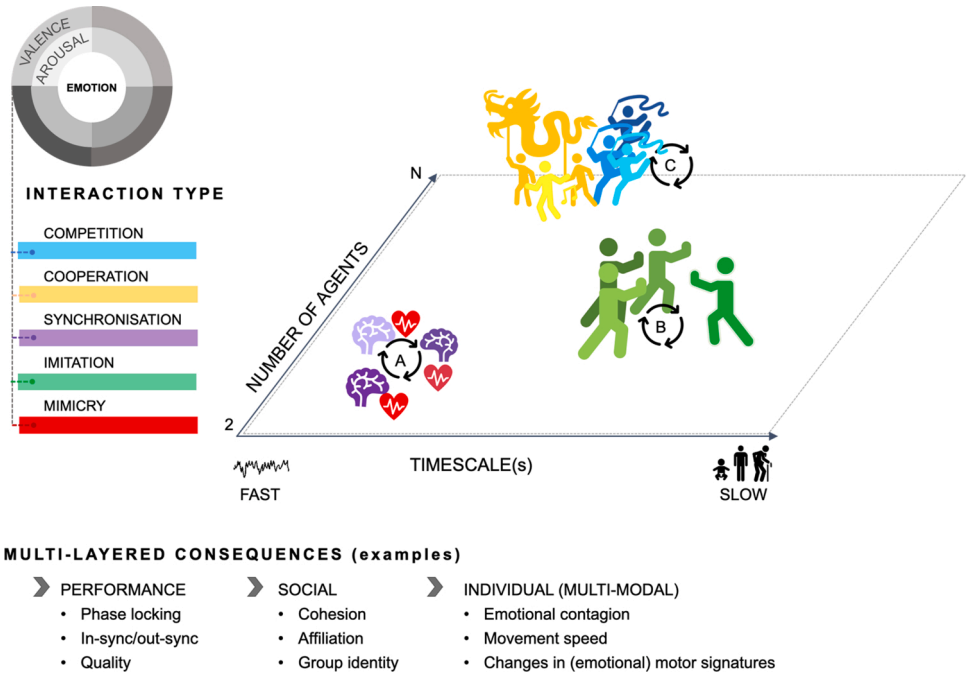


Fig. 5. Presentation of the future research landscape for emotion and joint action. **The bottom horizontal axis** represents **multiple timescales** that can be extracted from data (ranging from *ms*, i.e. brain and neural activity, to *hours and years,* i.e. expertise). **The vertical axis** denotes the number of agents engaged in socio-motor interaction, being perceptually and motorically active in the same physical or virtual space. **The colorful legend on the left side** represents possible **types of socio-motor interaction** that emerged from the literature review (delineating different spatio-temporal relationships between agents - see Table 1 for summary). **The circle in the left corner** represents models of emotions (gradients relate to dimensions of valence and arousal) that need to be adapted to multiagent scenarios, and here are injected into a color scheme of interaction types. **Bottom panel** lists **multi-layered consequences** of **the socio-motor interaction** across three main categories: performance (quantitative and qualitative), social (i.e., affiliation and cohesion) and individual (impact on personal motor characteristics and emotional contagion from interaction with other agents), identified from this review. Example A – recordings of brain activity (hyper scanning) and heart activity during a naturalistic conversation between three people; Example B—A group is trying to follow and repeat the pattern from the leader (Tai Chi class), captured with motion and respiration recordings; Example C – Group of agents dancing in and out of synchrony with each other (music street festival/parade), intertwined with periods of coordinated competition with each other, captured with motion recordings, following different typologies (Bardy et al., 2020). *Images: The Tai Chi and Old Man icons come from* http://www.flaticon.com *(author: Freepik).*

social and individual.

Recent models of emotion (i.e., Barrett, 2017b) have paved a theoretical path to integrate aspects of the presence of others and acting together in order to bridge a new, more informed, interdisciplinary avenue of research that is inclusive of dynamic relationships between emotion and joint action performance, when more than one agent is present, and of action context. The scientific evidence gathered and synthesized in Sections 1–3 of this review provides a weighty incentive to embrace more holistic and interdisciplinary approaches that are built on the assumption that our brain is primarily predictive, over reactive, and that our emotions are based of interoception and exteroception, and play an important allostatic function. Human abilities to understand emotions and to act together develop simultaneously throughout the lifespan and show neural overlap in brain activity suggesting that both have been shaped by evolution to be interdependent. Therefore, the unraveling of the intrinsic relationship between emotion and socio-motor interaction needs to be built on modeling multi/inter-modal emotion propagation models, conceptualizing what group emotion is, and whether some emotions are exclusive to interaction (see Fig. 6).

This will nourish new modes of social interaction with non-human agents, which can provide personalized care, entertainment and lifelong education for fragile populations. We argue that the deployment of machine learning algorithms and models supporting multiple timescales might provide the apposite caliber of research machinery to advance our comprehension of the dynamics of this ‘dark matter’

OUTSTANDING QUESTIONS

- How do individual emotions shape the way we move during joint action?
- Does joint action require agents to tune into the emotional state of other group members via empathy or to acknowledge it via mimicry?
- How can we track multi(/inter)-modal propagation of emotional embodiment (i.e. qualities/features)?
- Are certain emotions amplified by being with others while other emotions are exclusive to being with others (i.e., timidness, shame or desire)?

Fig. 6. Questions we have not found answer to during our literature review and need to be addressed by inter-disciplinary research.

(Schilbach et al., 2013), and dissect the multi-layered physiological, socio-behavioral consequences of acting together, inclusive of the emotion component and cohesion between agents. Progress in this cross-disciplinary field will feed future research and development in many technological areas such as collaborative robotics for industry and healthcare (i.e., incorporating the design of artificial agent principles, sensors and effectors for social-signaling and sensori-motor communication), and will provide the tools for embodied digital interactions (for virtual workspaces and education).

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Appendix A

Keywords (acting together)	Keywords (emo)
joint action	emotion *
acting together	
acting in unison	
moving in unison	
moving together	Keywords (clinical)
group movement	Autism
group synchronisation	ASD
action coordination	Autistic
social motor coordination	Alexithymia
action cooperation	
entrainment	
action coupling	
motor coupling	
group imititation	
motor mimicry	
action mimicry	
propagation	
synchronisation	
chameleon effect	
synchrony	

PUBMED SYNTAX/ MAIN SEARCH	REVELANT HITS (repetitions were ignored ignored from the count)
(group movement [Title/Abstract]) AND emotion [Title/Abstract]	0/5
(group synchronisation [Title/Abstract]) AND emotion [Title/Abstract]	1/5
(synchronisation [Title/Abstract]) AND emotion [Title/Abstract]	3/24
(moving in unison [Title/Abstract]) AND emotion [Title/Abstract]	0
(moving together [Title/Abstract]) AND emotion [Title/Abstract]	4/78
(acting in unison [Title/Abstract]) AND emotion [Title/Abstract]	0/64
(acting together [Title/Abstract]) AND emotion [Title/Abstract]	2/2
(action coordination [Title/Abstract]) AND emotion [Title/Abstract]	1/1
(social motor coordination [Title/Abstract]) AND emotion [Title/Abstract]	1/39
(action cooperation [Title/Abstract]) AND emotion [Title/Abstract]	1/1
(motor coupling [Title/Abstract]) AND emotion [Title/Abstract]	0/2
(action coupling [Title/Abstract]) AND emotion [Title/Abstract]	2/5
(motor mimicry [Title/Abstract]) AND emotion [Title/Abstract]	2/11
(action mimicry [Title/Abstract]) AND emotion [Title/Abstract]	8/27
(group imitation [Title/Abstract]) AND emotion [Title/Abstract]	5/46
(entrainment [Title/Abstract]) AND emotion [Title/Abstract]	5/97
(joint action [Title/Abstract]) AND emotion [Title/Abstract]	0/5
(propagation [Title/Abstract]) AND emotion [Title/Abstract]	0/33
(Interpersonal coordination [Title/Abstract]) AND emotion [Title/Abstract]	5/25
(chameleon effect [Title/Abstract]) AND emotion [Title/Abstract]	2/2
(group synchronization) AND emotion [Title/Abstract]	3/96
(motor synchronization) AND emotion [Title/Abstract]	2/57
((emotion[Title/Abstract]) AND synchrony[Title/Abstract]) AND (motor[Title/Abstract] OR movement[Title/Abstract] OR motion[Title/Abstract])	11/17

PUBMED SYNTAX/ CLINCIAL SEARCH

AUTISTIC SPECTRUM DISORDER

((autism[Title/Abstract] OR autistic[Title/Abstract])) AND (joint action[Title/Abstract] OR synchronisation[Title/Abstract] OR chameleon effect[Title/Abstract] OR synchronization[Title/Abstract] OR propagation[Title/Abstract] OR action mimicry[Title/Abstract] OR motor mimicry[Title/Abstract] OR group imitation[Title/Abstract] OR motor coupling[Title/Abstract] OR action coupling[Title/Abstract] OR entrainment[Title/Abstract] OR action cooperation[Title/Abstract] OR social motor coordination[Title/Abstract] OR action coordination[Title/Abstract] OR group synchronisation[Title/Abstract] OR group movement[Title/Abstract] OR moving together[Title/Abstract] OR moving in unison[Title/Abstract] OR acting in unison[Title/Abstract] OR acting together[Title/Abstract] OR group synchronization[Title/Abstract])	40/ 441
((autism[Title/Abstract]) AND synchrony[Title/Abstract]) AND (motor[Title/Abstract] OR movement[Title/Abstract] OR moving[Title/Abstract])	8/42

ALEXITHYMIA

((alexithymia[Title/Abstract] OR alexithymic[Title/Abstract])) AND (joint action[Title/Abstract] OR synchronisation[Title/Abstract] OR chameleon effect[Title/Abstract] OR synchronization[Title/Abstract] OR propagation[Title/Abstract] OR action mimicry[Title/Abstract] OR motor mimicry[Title/Abstract] OR group imitation[Title/Abstract] OR motor coupling[Title/Abstract] OR action coupling[Title/Abstract] OR entrainment[Title/Abstract] OR action cooperation[Title/Abstract] OR social motor coordination[Title/Abstract] OR action coordination[Title/Abstract] OR group synchronisation[Title/Abstract] OR group movement[Title/Abstract] OR moving together[Title/Abstract] OR moving in unison[Title/Abstract] OR acting in unison[Title/Abstract] OR acting together[Title/Abstract] OR group synchronization[Title/Abstract])	1/9

SCHIZOPHRENIA

schizophrenia[Title/Abstract] AND (joint action[Title/Abstract] OR synchronisation[Title/Abstract] OR chameleon effect[Title/Abstract] OR synchronization[Title/Abstract] OR propagation[Title/Abstract] OR action mimicry[Title/Abstract] OR motor mimicry[Title/Abstract] OR group imitation[Title/Abstract] OR motor coupling[Title/Abstract] OR action coupling[Title/Abstract] OR entrainment[Title/Abstract] OR action cooperation[Title/Abstract] OR social motor coordination[Title/Abstract] OR action coordination[Title/Abstract] OR group synchronisation[Title/Abstract] OR group movement[Title/Abstract] OR moving together[Title/Abstract] OR moving in unison[Title/Abstract] OR acting in unison[Title/Abstract] OR acting together[Title/Abstract] OR group synchronization[Title/Abstract])	15/539
((schizophrenia[Title/Abstract]) AND synchrony[Title/Abstract]) AND (motor[Title/Abstract] OR movement[Title/Abstract] OR	0/28

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Summary of Chapter 6

While emotion and joint action have traditionally been studied independently, a growing body of evidence highlights their interrelated nature. Recognizing this interconnection, there is a pressing need to integrate these two separate research strands to achieve a comprehensive understanding of human behavior in social contexts. Moreover, we demonstrated that the integration of the two research strands opens up avenues for developing more ecological models of interpersonal synchronization that take into account the emotions that guide individuals in their environment. While advancements in dyad research have yielded substantial evidence regarding the social implications of interpersonal synchronization, the investigation of dynamics on the scale $N > 2$ remains vastly understudied.

Most models of emotion are individualistic and do not take into account the dynamics and group processes of the functional meaning that the context includes. Regardless of the context, emotional expressions exhibited through behavior, facial expressions, or physiological states do not align in a one-to-one manner with specific discrete emotional states, such as joy or sadness. In other words, these manifestations of emotion cannot be easily and definitively attributed to a single, distinct emotional state. This myriad ways of expressing the same emotion is particularly challenging for individuals diagnosed with schizophrenia and Autism Spectrum Disorder. These individuals often experience challenges in recognizing and interpreting emotions and intentions and are characterized by an atypical neural activity of the mirror neuron system. Some promising early evidence is emerging about the efficacy of therapies based on synchronization and imitation training targeting the mirror neuron system and its related processes for enhancing emotion recognition.

Currently, Human-Robot and Human-Computer Interactions are primarily focused on encoding and conveying positive and comforting emotions through stereotypical expressions, and sounds. These expressions are tailored to specific contexts, such as individuals diagnosed with Autism Spectrum Disorder or the elderly, to serve their unique needs and requirements. Nevertheless, the formidable challenge that lies ahead is the ability to accurately detect the emotional state of the person with whom interaction takes place, and subsequently respond and encode emotions through the agent's facial expressions, movements, and sounds. The complexity of this task is further heightened when considering the multi-person context in which artificial intelligence (AI), in the form of a robot or computer, is designed to accommodate the diverse needs of several individuals simultaneously.

Building upon the literature review conducted in this study, we put forth the following directions for future research. First, rather than seeking typical emotional expressions

in behavior, there is a need to derive the idiosyncratic movement qualities that provide indications of underlying emotions, what we call emotional signatures. Second, it is essential to integrate emotions and their associated action tendencies into models of interpersonal synchronization. Third, we encourage the community to investigate the various temporal scales that underlie the human experience and functioning. Fourth, explore the potential of utilizing machine learning methods to unlock opportunities for generating valuable insights and enhancing emotion recognition in social interactions. Fifth, examine how interactions within virtual spaces acquire novel significance and give rise to unique affordances that influence the transmission of emotional qualities and shape the nature of collaborative interactions.

During our theoretical review, we identified several critical outstanding questions, with one particular question taking precedence in my PhD program: the experimental investigation of the effect of emotions on joint action.

CHAPTER 7

Theme 2: Methodological

This chapter presents Publication № 4[1]: **Smykovskyi**, A., Bieńkiewicz, M. M. N., Janaqi, S., and Bardy, B. G. (2023). *In preparation*.

The fourth publication explored the conceptualization of interpersonal synchronization using four tasks. First, we review methodological studies that educate on the application of synchronization analyses. Specifically, the studies are divided into two main categories: the proof-of-concept articles that propose the use of one specific method in one specific context, and comparative articles that compare multiple analytical methods in the same context.

Second, we highlight the problem of disparate conceptualizations of interpersonal synchronization. Namely, we dissect the causes of some disputes between scientists, such as the existence of menstrual synchrony in females that live together, the adaptive value of sleep-wake cycle synchronization between animals, or the synchronization of movements between mother and the infant to explain children's development.

Third, we analyze dimensions that help assess and interpret interpersonal synchronization. For this task, we built upon the Burgoon's et al. (1995) framework for interpersonal adaptation and used the following dimensions: directedness, behavioral contingency, direction of influence, tendency towards change or maintenance, magnitude versus direction, intentionality, and functional behaviors. In addition, we enrich each of the dimensions with empirical and theoretical evidence from the psychological, social, and movement sciences.

Fourth, we plan to depict the accuracy of various methods of interpersonal synchronization measurement applied to data of various characteristics. In-phase, anti-phase, phase-locked, and non-periodical time series data are analyzed and compared using various linear and nonlinear methods, as well as through time and frequency domains.

[1]The publications are numbered in chronological order but to ensure the logical flow between research themes, we insert the last publication within the second research theme.

Measuring interpersonal synchronization: Approaches to operationalization and techniques for analysis

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Abstract

The phenomenon of synchronization marvels researchers across different scientific disciplines. Physicists model the behavior of coupled oscillators, biologists interpret changes in circadian rhythms, and neuroscientists track down the foci of epileptic seizures. In the last decades, synchronization has attracted the interest of psychologists who endeavor to explain the emergent processes of the human mind through interpersonal behavior. But despite the prominence of synchronization experiments in psychological research, the operationalization of the phenomenon has rarely been scrutinized as a dynamical process. Instead, synchronization is compressed into mere coinciding events (i.e., synchrony), or even to coarse similarity of signals. In this paper, we evidence examples in which the lack of consensus on what constitutes synchronization leads to conflicting conclusions hindering scientific progress. Moreover, various dimensions of quantifying interpersonal synchronization are discussed. Our main objective was to present time series of different nature (i.e., in-phase, anti-phase, phase-locked, non-periodical) and develop reader's intuition for the accuracy of the main quantification methods of interpersonal synchronization (e.g., cross-correlation, wavelets, phase, and recurrence quantification analyses). Finally, we demonstrate the utility of *Kuramoto order parameter* analysis to detect the movement of in and out of synchrony (i.e., synchronization) and its limitations for application in psychological research.

Keywords

Synchronization method, interpersonal synchronization, joint action, Kuramoto order parameter, multimodal analysis

Introduction

How to detect and seize interpersonal synchronization? The question is oftentimes narrowed down to the mere detection of perfect harmony of rhythms, but synchronization is a more intricate and nuanced phenomenon than just unison. It encompasses the complex process of rhythm adjustments among agents, requiring researchers to possess a comprehensive understanding of its underlying components and expertise in effectively employing analytical methods. Extensive literature spanning various scientific disciplines has explored the pervasive occurrence of synchronization, with each field serving its unique purpose in analyzing synchronization. Therefore, it is unsurprising that different scientific disciplines employ disparate analytical approaches to evaluate and interpret synchronization. Due to this divergence in measurements, the notion of synchronization itself becomes unclear and ambiguous.

Experts in psychological researcher have shown growing interest in synchrony due to its ability to explain various socio-emotional processes that emerge when individuals coordinate movements in time with one another (e.g., Bernieri et al., 1994; Feldman, 2007; Hove & Risen, 2009; McNeil, 1995; Ramseyer & Tschacher, 2011). However, participating in mirrored and synchronous interaction is not always advantageous, as alternative strategies, such as undertaking divisible or antagonistic tasks (e.g., Jarrassé, Charalambous, & Burdet, 2012), can be more beneficial. This is supported by empirical studies conducted by Abney et al. (2015), Vink et al. (2017), and Wallot et al. (2016). Nevertheless, it is crucial to recognize that synchrony between individuals represents a fundamental and automatic biological process, whereby one's behaviors and emotions are naturally perceived and mirrored by others (Burgoon, 1995). This emphasizes that synchrony is not merely an outcome of interaction, but rather a mechanism that drives it (Strang et al., 2013). Therefore, it is essential to capture the dynamics of interpersonal synchrony, and recent evidence supports the use of more dynamic methods that can effectively capture the processes of coupling and uncoupling during social interactions (Dumas & Fairhurst, 2021; Mayo & Gordon, 2020).

Effectively capturing the dynamics of interpersonal synchrony poses a significant and formidable challenge. In a recent contribution to the prestigious journal *Nature*, Ravignani (2017) initiated an interdisciplinary debate regarding the necessity to establish a consensus on the definitions of synchrony. Ravignani proposed adopting the definitions of synchrony employed in mathematics and physics as a means to distinguish it from other forms of "looser co-occurrence". Furthermore, Schirmer, Fairhurst, and Hoehl (2021) emphasized the importance of gaining a deeper understanding and promoting the convergence of findings in the field to achieve higher levels of alignment in research outcomes. This need for convergence arises from the increasing methodological diversity encompassing various measurement techniques and approaches to data interpretation. It is beneficial to examine the justifications presented by researchers in order to better understand the selection of methods utilized for measuring synchronization.

The practice of providing a detailed justification for the selection of a synchronization measurement technique and its suitability for the specific characteristics of the data at hand is relatively uncommon. For instance, one example of a synchronization method is cross recurrence quantification analysis, which proves advantageous due to its ability to handle data without making assumptions about the nature of data and its usefulness in capturing the complexity of postural sway (Shockley et al., 2005). Another example is the use of cross-recurrence quantification analysis to capture coordination in cardiac signals, which may not be captured effectively by averaging methods such as correlations (Konvalinka et al., 2011). Additionally, multidimensional cross-recurrence quantification analysis has been employed to approach groups as more than just the sum of their subparts, enabling the capture of group-level processes (Tomashin, Gordon & Wallot, 2022). Furthermore, a five-step adjustment technique has been utilized for nonstationary time series, allowing the quantification of phase synchronization with the Kuramoto order parameter analysis for capturing the dynamics of interpersonal synchronization in movement and cardiac data (Smykovskyi et al., 2022). Given these circumstances, it becomes necessary to explore more in depth the various methodological publications that assist in the selection of an appropriate method.

Related Work

Numerous synchronization measurement techniques have been implemented and documented in peer-reviewed literature. These methods encompass a range of analytical tools, such as windowed cross-correlations (e.g., Ashenfelter et al., 2009), cross-wavelet analysis (e.g., Issartel et al., 2014), and intricate multidimensional cross-recurrence analysis (e.g., Wallot, 2019). However, for professionals without a strong

technical background, making an informed decision about which synchronization measurement method to use can be challenging. We begin this manuscript by presenting a review of two types of interpersonal synchronization methodological publications that involve the operationalization and comparison of various measurements. First, we explore articles where authors provide arguments regarding the efficacy of specific synchronization quantification methods (i.e., proof-of-concept articles). Second, we examine articles where authors describe and contrast several synchronization quantification methods (i.e., comparison articles). It is important to note that our intention is not to provide an exhaustive analysis of all available methods, but rather to provide an overview that captures the key insights offered by different methodological strategies.

Proof-of-concept articles

Automated measures of synchrony offer a clear advantage over synchrony measures provided by human coders (Dunbar, Burgoon & Fujiwara, 2022; Schmidt et al., 2012). One such technique is the quantification of **behavioral synchrony from videos**. A key benefit of this method is its accessibility, as it does not require substantial financial investments such as expensive motion capture systems. This affordability can assist in alleviating the laborious task of manually analyzing data with human observers. For example, the motion energy analysis technique quantifies differences in pixels within the grayscale hue over successive frames (Kleinbub & Ramseyer, 2021). They have developed an R package to assess nonverbal synchronization in motion energy analysis time series. This method allows for the analysis of multiple regions of interest, enabling the simultaneous examination of several individuals. Another approach is presented by Paxton and Dale (2013), who introduced a Matlab-based method for analyzing videos of dyads engaged in conversation. Specifically, they utilized the frame-differencing method, which objectively quantifies interpersonal bodily synchrony by analyzing pixels. Unlike the motion energy analysis method (e.g., Ramseyer & Tschacher, 2011), the frame-differencing method does not require the indication of specific regions of interest. Moreover, it demonstrates robustness to slight fluctuations in light sources but is sensitive to slight movements. Following image processing, calculations were performed to obtain average, highest, and lowest synchrony scores, which can be then analyzed as correlation coefficients. However, video analysis methods do have certain drawbacks, particularly in their ability to analyze only two-dimensional movements. Although the level of precision is often sufficient for many applications, it may not provide the desired level of accuracy in more intricate or detailed analyses.

Various synchronization methods are employed to quantify **physiological synchrony**, often utilizing correlational **linear measures**. Tschacher and Meier (2020) conducted a study in which they measured physiological synchrony, including ECG, respiration, HR, and HRV, using windowed cross-correlation (surrogate Synchrony, SUSY) and correlation of local slopes (surrogate concordance, SUCO, representing window-wise regression slopes). To determine the presence of synchrony, the obtained results were compared to the results of shuffled pairs, as demonstrated with the SUSY approach, establishing a ground truth for the presence of synchrony. Moreover, Behrens et al. (2020) utilized windowed cross correlation metrics, including parameters such as window size, lag, and window and lag increment. They applied these metrics to various physiological modalities, such as heart rate, skin conductance level, pupil size, and facial expressions data. The objective is to compare real pairs with shuffled pairs. The results demonstrated that with smaller window sizes yielded the highest accuracy in discrimination. Liu, Zhou, Palumbo, and Wang (2016) introduced a novel method called Dynamical Correlation, which surpasses the limitations of quantifying mere Pearson correlation. This method is particularly valuable when dealing with autocorrelated data, where subsequent values depend on previous values in time. Autocorrelated time series violate the assumption of data independence, and relying on Pearson correlation in such cases can lead to erroneous outcomes.

Alternative methods have been developed for detecting **physiological synchronization** that depart from linear correlational measures and explore **nonlinear measures**. For instance, Gates et al. (2015) employed the tapering method (Hanning window) to estimate Respiratory Sinus Arrhythmia in husband-wife dyads. Furthermore, Helm et al. (2012) analyzed measures of respiration and heart rate in romantic couples, utilizing a Coupled Linear Oscillator model to identify covariation in physiological signals. These approaches highlight the utilization of nonlinear methods to capture the dynamics of physiological synchronization in different relational contexts. In their study, Wallot et al. (2013) examined the sensitivity of various complexity metrics on RR intervals (the time interval between two successive heartbeats) and regular beats per minute (BPM) heart rate measures. The nonlinear analysis demonstrated a high level of performance when applied to RR intervals. However, the accuracy slightly decreased when applied to smoothed BPM measurements, although it was restored when BPM was oversampled. Several helpful and pedagogical tutorials are available to assist in the implementation of various variations of recurrence quantification analysis, as well as assisting in parameter selection (Wallot, 2017; Wallot & Mønster, 2018; Wallot & Leonardi, 2018; Wallot, 2019).

Comparison articles

Within methodological articles, interpersonal synchronization analyses can be classified in diverse ways, presenting a range of approaches that enable the comprehension of the phenomenon. For instance, linear and nonlinear analyses (Strang et al., 2013), time and frequency analyses (Delaherche et al., 2012), convergence of time and convergence of rhythm (Dunbar, Burgoon & Fujiwara 2022), or even aggregate (i.e., averaging), separate (i.e., machine learning methods that disregards temporal dynamics), describe (i.e., qualitative methods), linearize (i.e., regression), and nonlinear dynamic analytical approaches (Knight et al., 2016). For a more comprehensive exploration of various analyses, specifically the 249 metrics utilized for assessing dyadic interaction, refer to the work of Cliff et al. (2022). In a helpful tutorial, Cheong (2019) compared four widely recognized approaches for quantifying synchrony, which we adopt as a framework for presenting the various methods employed in research. These methods include: i) Pearson correlation, ii) time-lagged cross correlation (TLCC) & windowed TLCC (WTLCC), iii) dynamic time warping (DTW), and instantaneous phase synchrony. We will examine each of these methods sequentially.

First, the Pearson correlation measure captures the covariation between two signals and is appreciated for its simplicity in implementation and interpretation. However, this method is sensitive to outliers and assumes homogeneity or similarity of variance (i.e., homoscedasticity). Additionally, its most significant drawback that it provides a restricted perspective by presenting a *global* assessment of overall synchrony, condensed into a single variable. Consequently, it overlooks the temporal dynamics of the signals, disregarding the unfolding changes that occur over time. Alternatively, it is possible to examine the *local* synchrony by using rolling windows of a defined size and calculating the Pearson correlation within each window. Moreover, the Pearson correlation does not provide the direction of influence. In this light, cross-correlation serves as a valuable extension that can be utilized to determine the order of occurrence between signals. It is important to stress, however, that cross-correlation cannot establish causality between the signals (Cheong, 2019). Correlational measures only extract two parameters: the strength of the relationship and its direction (Delaherche et al., 2012).

Second, TLCC method involves iteratively shifting one signal and calculating the correlation between signals at each shift. This allows for the identification of signal offsets and the inference of leader-follower interactions across the entire signal. Moreover, by measuring TLCC in multiple windows within the time series (i.e., WTLCC), it enables the analysis and intuitive visualization of the dynamic changes and shifts in

leader-follower roles within the dyad over time. However, this approach relies on the assumption that events occur at the same time and have equal durations (Cheong, 2019). Schoenherr et al. (2019) compared seven distinct types of linear time series (correlation) measures and found that these measures do not encompass the same notion of synchrony. Indeed, the metrics offer valuable insights into specific aspects of interaction, encompassing i) complete interaction, ii) intervals, iii) frequency, and non-linear synchronization.

Third, DTW calculates the Euclidean distance between each frame of one signal and every other frame of the other signal. It then identifies the minimum path that aligns these two signals, enabling the analysis of signals with varying lengths. However, when dealing with missing data, signal interpolation is necessary to fill in the gaps and ensure accurate results (Cheong, 2019). The method finds application in studying multimodal structures of discourse, including gestures and vocalizations exchanged between two individuals. Pouw and Dixon (2020) extended the use of DTW and introduced a gesture network analysis that holds the potential to provide insights into how low-level features, such as gesture movement qualities, can offer valuable information about higher-order structures at the discourse level.

Fourth, instantaneous phase synchrony quantifies the moment-to-moment synchronization between oscillating signals by extracting their phases, often accomplished using methods like the Hilbert transform. It then assesses the degree of phase correspondence between the signals, such as in-phase or anti-phase relationships. However, when applying this approach to functional brain data, it is necessary to employ filtering techniques and provide theoretical justifications or reasons to emphasize specific wavelength ranges. This ensures that the analysis focuses on the desired frequency bands and maintains relevance to the research objectives (Cheong, 2019). Furthermore, Delaherche et al. (2012) introduced spectral methods for examining the dynamics of the relative phase between two signals. They proposed two methods: i) Stability, represented by a histogram of the relative phase throughout the entire interaction, which indicates the level of flatness in the distribution; and ii) Cross-spectral coherence, which assesses the overlap between movement frequencies by identifying the intersection area between the normalized spectral plots. In this light, cross-spectral coherence can be utilized to evaluate strength of synchronization, whereas the continuous relative phase allows to determine the pattern of synchronization (Schmidt et al., 2012). In the time domain, the Cross-Wavelet Transform assesses the level of synchrony and its temporal changes, even in non-stationary and non-harmonic time series (Issartel et al., 2014).

Over the past decade, there has been increasing evidence supporting the usefulness of an alternative method known as recurrence quantification analysis (RQA). The analysis involves interpreting recurrence plots by utilizing various metrics to calculate the nature of the recurrences. In this analysis, specific metrics such as %REC (percentage of recurrent points on the recurrence plot), %DET (percentage of determinism based on diagonal structures), and ENTR (entropy reflecting the complexity of the deterministic structure) are utilized (Delaherche et al., 2012). In other cases, another metric of interest is LAM, which reflects the presence of adjacent vertical line structures. In contrast to %DET, which may be more suitable for deterministic structure of the signal, LAM provides valuable insights in stochastic signals (Wallot et al., 2016). Yet, despite their demanding computational nature, the results obtained from joint RQA often exhibit comparable findings to those obtained through cross-correlational analyses (Tolston et al., 2020).

The aforementioned methods provide a broad overview of different approaches for synchronization analysis. However, a crucial question remains unanswered: which methodologies are best suited for different types of data? Surprisingly, this question has not been thoroughly addressed in research, despite its importance in selecting the most appropriate analysis method for a given dataset. It was only recently, that Hudson et al. (2023) tested multivariate nonlinear methods accuracy for synchrony detection on synthetic signals with varying levels of coupling (i.e., weak and strong). However, what still lacks is a comprehensive discussion

and the precise definition of synchronization and, more importantly, an exploration of how different methodological approaches perform on data with distinct characteristics. This includes examining the performance of these approaches on in-phase versus anti-phase signals. Furthermore, Strogatz (2003) emphasized that the study of coupled oscillators has primarily focused on mono-frequential oscillators and warned that human behavior and physiology can exhibit multiple frequencies simultaneously. This paradigm shift presents a notable challenge and necessitates additional research to explore methods capable of capturing synchronization in multi-frequential signals, in contrast to the more straightforward mono-frequential signals. These are the very questions that this paper aims to explore.

Synchronisation and Its Properties

How to study interpersonal *synchronization*? To understand and operationalize synchronization, we must clearly disentangle it from other notions, such as *entrainment*. However, the conceptual understanding of *synchronization* and *entrainment* vary across different scientific disciplines "reflecting the background, individual viewpoints and taste of a researcher" (Pikovsky et al., 2001, p. 22).

Multidisciplinary definitions of synchronization

Applied mathematician Strogatz (2003) stipulated that synchronization occurs at three levels in the hierarchy of living oscillators and exemplified the levels with changes in circadian rhythms. At the first microscopic level, the cells within an organ synchronize. At the second level, synchronization occurs between the organs within the body. At the last level, synchronization emerges between the body and its environment. This last level Strogatz calls *entrainment*, which reflects the "process of external synchronization, of falling in step with the outside world" (Strogatz, 2003, p. 72). Therefore, when talking about interpersonal synchronization from the mathematics perspective in which each other individual is considered as an external system, the words *entrainment* and *synchronization* can be used interchangeably.

However, the notion of *entrainment* acquires different meaning in the context of life sciences. Zoologist Mrosovsky (1999) juxtaposed *entrainment* to *masking* to explain the behavioral and physiological activity of species during the day. In essence, the difference between the two phenomena is whether the environmental illumination modifies the suprachiasmatic nucleus of the hypothalamus–the internal pacemaker–that in turn changes the physiological and behavioral rhythms (i.e., *entrainment*) or the environmental illumination modifies the rhythms directly (i.e., *masking*). Thus, as opposed to the mathematics perspective in which entrainment is rhythm adjustments to external stimuli, biologists assert that entrainment reflects internal synchronisation. More recently, Bittman (2021) built upon Mrosovsky's work and compared *entrainment* and *synchronization* and published an article with the eye-catching title "Entrainment is NOT synchronization: an important distinction and its implications" in which he defended that synchronization is restricted exclusively to systems with zero phase difference between oscillators' rhythms. Furthermore, Bittman (2021) affirmed that synchrony could be detrimental to species survival. For instance, if animals of different social rank that normally look for food at different times of the day would suddenly have coinciding sleep-wake cycles, the low rank animals would struggle to survive. In the pursuit of clarifying the important adaptive value of a flexible internal pacemaker, the biological perspective renders the concepts of *entrainment* and *synchronization* fuzzy for generalization to other scientific fields.

The misleading operationalization of what constitutes *synchronization* in the life sciences is not limited to the circadian rhythm, but is also present in the debate about whether women synchronize their menstrual cycles.

McClintock (1971) investigated women living together in a college dormitory and found that the individual median difference in the onset of menstrual cycles was reduced from 8.5 to five days in only four cycles. But what exactly can account for drifts in hormonal activity? Russel et al. (1980) studied the role of olfactory cues for changes in menstrual cycles. For this purpose, they created an "essence of Genevieve" which is a mix of alcohol and sweat of a donor. In the experiment, one group of female participants applied the "essence of Genevieve" on the upper lip three times a week during four months and the control group applied only alcohol with the same frequency. While there were no meaningful differences in the control group, results from the experimental group revealed that the difference in the onset of menstrual cycles dropped from 9.3 to a staggering 3.4 days in only five cycles. Can we interpret shortened differences in the menstruation onset from 8.5 to five days and from 9.3 to 3.4 days as evidence of menstrual synchronization? If we operationalize synchronization as coinciding events, no. For this reason, it is not surprising that the research that refuted menstrual synchronization defined it as "the matching of cycle onsets over time, once established it should persist." (Ziomkiewicz, 2006, p. 419) and searched for "subtle statistical clusterings of cycle onsets" (Yang & Schank, 2006, p.435). In this light, the results of the research conducted by McClintock (1971) and Russel et al. (1980) suggest that the menstrual cycles are *not* in synchrony, but they *are* synchronizing. Therefore, it turns out the debate about whether menstrual synchronization occurs is, in part, a disagreement on how to operationalize *synchronization* as rhythm adjustments or as coinciding events. Generating a shared operationalization of the concept and addressing methodological concerns (see Strassman, 1999) will help to resolve the controversy over menstrual synchronization.

Operationalization discrepancy of what constitutes *synchronization* is preserved in social science research. The pioneering efforts of Condon and Ogston (1966) to use movie films to quantify patterns (i.e., configurations) of behavioral change initiated a new line of research in the analysis of how the rhythm of the speaker's body movements influences the rhythm of the listener's movements. Condon and Ogston referred to harmonious "configurations of change" as interactional synchrony. Early critiques (McDowall, 1978) challenged the existence of the phenomenon arguing that the empirical evidence represented below chance levels of coinciding events. However, Gatewood and Rosenwein (1981) defended that McDowall misinterpreted Condon and Ogston's operationalization of interpersonal synchrony by defining synchrony as temporal coincidence and the presence of a delay as absence of synchronization. Moreover, Lynn (1996) also restricted movement synchrony to simultaneity or a maximum delay of 0.2 seconds between the onset of events and concluded that movement synchrony is a myth. Taken together, the critiques of behavioral synchronization fail to draw a clear distinction between synchrony, as a state of persisting and coinciding events, and synchronization, as a process reflected in a tendency towards converging rhythms. Considering that some of the aforementioned research fields developed their synchronization tools on the basis of physics and the science of coupled oscillators, it appears necessary to get back to the fundamentals to overcome the controversies.

Definition of synchronization and its dimensions

Physicists Pikovsky and colleagues (2001) wrote a separate subsection in their seminal work to clarify terminology because the use of notions *synchronization* and *entrainment*. In contrast to the social science research, Pikovsky and colleagues (2001) specified *entrainment* as "the constant phase shift and (small) fluctuations of the phase difference". The authors insisted that in physics, *synchronization* does not only mean the complete coincidence of signals, but define synchronization as rhythm adjustments due to interaction.

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Summary of Chapter 7

In this article, we substantiated the call for agreeing on the definition of interpersonal synchrony, opened in the prestigious journal Nature, that overlooking the dynamical essence of synchronization leads to debates in various scientific fields.

In the assessment of methodological articles on interpersonal synchronization (i.e., proof-of-concept and comparative articles), we determined that although there are studies comparing different evaluation methods of synchronization on the same time series data, current accounts fail to provide insight into the performance of the same method for estimating synchronization on time series with different characteristics. Therefore, we plan to present several methods, quantified their performance on the data with different characteristics, and juxtaposed their outcomes.

Also, following Burgoon et al.'s (1995) framework, we plan to map out seven dimensions for calculating interpersonal synchronization. In addition, given the empirical evidence found in this thesis dissertation, we argue that emotions represent the order parameter of social interaction.

CHAPTER 8

Theme 3: Experimental 1.0

This chapter presents Publication № 2: **Smykovskyi**, A., Bieńkiewicz, M. M. N., Pla, S., Janaqi, S., and Bardy, B. G. (2022). Positive emotions foster spontaneous synchronisation in a group movement improvisation task. Frontiers in Human Neuroscience, 16, 944241. https://doi.org/10.3389/fnhum.2022.944241

The second publication (i.e., the first under the experimental theme) explored the effect of emotion on group synchronization in an unstructured experimental setting. Contrary to widely used and highly structured synchronization tasks (e.g., mirror game with movements in only one dimension), we attempted to achieve greater realism of social interaction and transcend the established priority of experimental control. Namely, groups of three participants completed an improvisational task with the possibility of movement in three dimensions of physical space. The inclusion of three-dimensional and expressive movement in the task enhances its representativeness of complex human joint behavior by mirroring the spatial realism, dynamic adaptability, and multifaceted coordination observed in real-life interactions.

In order to improve experimental control over the emotion induction method, standard methods sacrifice ecological validity. In this study, we developed an original method of emotion induction developed on the basis of success-failure manipulations. Fundamentally, the goals were i) to select a task and participants for whom the task is personally relevant (i.e., a dancing task for people who enjoy dancing), ii) to create a believable cover story (i.e., the participants will perform a dancing improvisational task and obtain a social comparison feedback), iii) to involve participants in the emotion induction procedure (i.e., rank the performance of all three group members in the previous trial), and iv) to convince participants in the trustworthiness of the performance feedback (i.e., perform a test voting before the experiment start and visualize the changes participant make with their vote).

Social interaction is a dynamical system in which a delicate interconnectedness exists between the elements of the system (e.g., between people in a group) as well as be-

tween its subsystems (e.g., between body movements and heartbeat of a person). Social researchers often endeavor to explain interaction dynamics through a single modality. However, this unimodal approach conceals the different processes that occur during social intercourse. The next stage in the evolution of social sciences requires a holistic understanding of synchronization processes at levels of systems and their subsystems. For this reason, we examined sensorimotor synchronization through a multimodal prism of analysis.

This work contributed to the Research Topic entitled "Interpersonal Synchrony and Network Dynamics in Social Interaction" which was opened in the Frontiers in Human Neuroscience journal. Empirical submissions from cognitive, computational, social, and system neuroscience were encouraged to submit to the Research Topic. Moreover, an emphasis on interaction within and between systems and subsystems was requested to explain the social interaction phenomenon (Interpersonal Synchrony and Network Dynamics in Social Interaction: About this Research Topic, no date). Our multimodal approach to social interaction, as well as computational analysis to test the effects of systematically induced emotions on interpersonal synchronization using the Kuramoto order parameter, matched the interest of the Research Topic. Therefore, we chose Frontiers in Human Neuroscience for this publication.

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Positive emotions foster spontaneous synchronisation in a group movement improvisation task

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Emotions are a natural vector for acting together with others and are witnessed in human behaviour, perception and body functions. For this reason, studies of human-to-human interaction, such as multi-person motor synchronisation, are a perfect setting to disentangle the linkage of emotion with socio-motor interaction. And yet, the majority of joint action studies aiming at understanding the impact of emotions on multi-person performance resort to enacted emotions, the ones that are emulated based on the previous experience of such emotions, and almost exclusively focus on dyadic interaction. In addition, tasks chosen to study emotion in joint action are frequently characterised by a reduced number of physical dimensions to gain experimental control and subsequent facilitation in data analysis. Therefore, it is not clear how naturalistically induced emotions diffuse in more ecological interactions with other people and how emotions affect the process of interpersonal synchronisation. Here, we show that positive and negative emotions differently alter spontaneous human synchronous behaviour during a multi-person improvisation task. The study involved 39 participants organised in triads who self-reported liking improvisational activities (e.g., dancing). The task involved producing improvisational movements with the right hand. Participants were emotionally induced by manipulated social feedback involving a personal ranking score. Three-dimensional spatio-temporal data and cardiac activity were extracted and transformed into oscillatory signals (phases) to compute behavioural and physiological synchrony. Our results demonstrate that individuals induced with positive emotions, as opposed to negative emotions or a neutral state, maintained behavioural synchrony with other group members for a longer period of time. These findings contribute to the emerging shift of neuroscience of emotion and affective sciences towards the environment of

social significance where emotions appear the most—in interaction with others. Our study showcases a method of quantification of synchrony in an improvisational and interactive task based on a well-established Kuramoto model.

KEYWORDS

interpersonal synchronisation, joint action, emotion, improvisation, non-verbal behaviour

Introduction

Rhythm entrainment is a social glue that helps humans to function and cooperate in large groups, constituting societies (Duranton and Gaunet, 2016). Since ancient times, people have engaged in rhythmic activities, such as singing or dancing, to improve their collective performances, such as hunting (von Zimmermann and Richardson, 2016). More recent historical records disclose that the introduction of synchronous drills into the Dutch Armed Forces in the late 16th century led to building a higher spirit of camaraderie and resulted in developing effective military units on the battlefield that altogether provided an edge for the Dutch army over other armies of the continent (McNeill, 1995). Interestingly, the drilling that made units more effective was believed to have established an emotional resonance between individuals. Consider this testimony of a person engaged in such drills: "Words are inadequate to describe the emotion aroused by the prolonged movement in unison that drilling involved. A sense of pervasive well-being is what I recall; more specifically, a strange sense of personal enlargement; a sort of swelling out, becoming bigger than life, thanks to participation in a collective ritual." (McNeill, 1995, p. 2). This quote draws attention to a surprising interplay between synchronous movements and human emotions, which is the object of the present study.

Synchronisation examples are everywhere around and inside us: from planets orbiting in different galaxies to fireflies firing in perfect unison to pacemaker cells in the human heart. The emergence of spontaneous order is a result achieved through order in space and time. While spatial ordering can be explained and demonstrated by the development of tangible and frequently understood architectures, temporal ordering is more elusive (Strogatz, 2003). For synchronisation to occur, several conditions must be met, such as the production of individual rhythm or oscillations, behavioural proximity, allowing for the exertion of physical or chemical influence and the coupling function (Strogatz, 2003). Fireflies communicate with flashing lights, have their inner rhythm, and adjust it in response to the flashing of others to attain synchronisation. In this light synchronisation analysis is based upon the extraction of individual frequencies and their relation to the group frequency, as well as the extraction of phases, i.e., moments where an event occurs in a time series (Pikovsky et al., 2001).

The phenomenon of human emotion intrigued ancient philosophers and has progressively transformed into a modern field of psychological research. However, the field is suffering from ongoing challenges. The realisation that "There will never be an integrative theory of emotion. . ." (Niedenthal and Brauer, 2012, p. 275) is a surprising way to start the conclusions section of recent Annals publication on the social functionality of human emotion. The difficulty is that there are myriad ways to approach the concept of emotions depending on research interests such as relevance for survival, the implication of cognition, morality, social engagement, or even the tendency for action that gives or seizes power. Despite some agreements on such essential topics as whether to approach emotion as discrete, separate entities (e.g., anger, surprise, and happiness) or in terms of dimensions (e.g., valence, arousal) as well as agreement on the distinction of emotion from other affective states (Ekman, 2016), there is no widely accepted definition after already 100 years of research (Russell, 2012). This poses a problem because the progress in studying a concept with fuzzy borders and subsequent experimental studies can be ineffective without an accurate and clear definition. Thus, it is of utmost importance when studying emotions to outline the aimed concept to explain. We phenomenologically understand emotions as relevance detectors occurring at behavioural, cognitive and physiological modalities that guide the decision process (Sander et al., 2003). Emotion interpretation as a relevance detector has essential consequences concerning the emotion induction method, which will be discussed in more detail in the relevant section. There is, however, an agreement (Sander, 2013) that emotions are a complex phenomenon resulting from clearly identified stimuli and followed by a reaction that brings about change not only in the cognitive modality but is expressed through other modalities as well, such as behaviour and physiology, of relatively short duration. This exemplifies the need to consider the different modalities of human experience for understanding emotions.

Previous research shows that there is a higher chance of losing rapport and creating misunderstandings in the absence of synchronous rhythmical movements. The rhythmic

convergence occurring spontaneously between people, without conscious and deliberate efforts to develop synchrony, was reported in experimental studies in which individuals, while sitting next to each other, tend to synchronise swings of their legs (Schmidt et al., 1990), rocking in chairs (Richardson et al., 2007), and side-by-side walking (Nessler and Gilliland, 2009). Interestingly, interpersonal motor synchronisation was found to increase social affiliation (Hove and Risen, 2009), enhance self-esteem (Lumsden et al., 2014), and develop the ability to cooperate (Valdesolo et al., 2010) and even improve tolerance to pain (Tarr et al., 2015). Once we understand the benefits of perceiving movement synchronisation, a logical question is how humans perceive synchronisation? In a dyadic Tai Chi experiment, it was found that the perception of phase synchrony, among other metrics such as mutual information or dynamical time warping, is the most prevailing metric humans use to identify synchronisation (Bente and Novotny, 2020). Continuing this line of thought, one might ask what comes first, is it the affect that causes improved synchronisation or is it the synchronisation that brings about a pleasant feeling? Fujiwara and Daibo (2018) found no evidence that changes in valence produced tangible changes in synchronisation levels. The authors supposed that one possible reason for the absence of effect is that emotion induction did not produce affective changes. Indeed, it is possible that watching parts of movies or specific picture sets, while being an effective induction procedure for some individuals, is not personally relevant when standardised for a multitude of different people. Even if the change in valence occurs, it does not automatically imply that emotion was evoked. Emotion does not only portray changes in valence (Quigley et al., 2014), which alone would describe mere changes in preferences (Scherer, 2005), but they activate special machinery acting through different modalities to prepare the body for the execution of specific actions (e.g., anger—to attack, fear—to run away, and sadness—to seek for help), the process referred to as action tendencies (Frijda, 2007).

The link between synchronisation and physiological arousal was empirically tested previously. For instance, watching a family member engaged in a dangerous activity, the heartbeat of both people tends to synchronise (Konvalinka et al., 2011). Similarly, during dialogue, the brain waves of the listeners tend to synchronise with the speaker's (Hasson and Frith, 2016). What is not yet clear is how the emotional state impacts motor synchronisation. Besides a handful of studies (e.g., Varni et al., 2010; Paxton and Dale, 2013; Tschacher et al., 2014; Fujiwara and Daibo, 2018), the link between emotion and synchronisation remains largely unexplored, and the results are inconsistent. For instance, while Fujiwara and Daibo (2018) did not find evidence for an influence of affective valence on synchrony in a dyadic interaction, Varni et al. (2010) documented that the positive emotion (i.e., pleasure) facilitated synchronisation within a group of musicians in comparison to the negative emotion (i.e., anger).

In a recent review (Bieńkiewicz et al., 2021), we emphasised the need for reconciliation between emotion and joint action research. In line with this proposal, this study aims to show the effects of experimentally induced emotional valence (positive emotion vs. neutral state vs. negative emotion) on group motor synchronisation (arm movements between three people). Given the exploratory nature of this work, we held no quantified expectation about the amount of interactional change following emotional induction but a general hypothesis about the direction of this relationship. Based on the state-of-the-art reviewed above, we expected that positive emotions would improve synchrony and that negative emotions would disrupt it.

Considerations for emotional induction in the lab

In this study, we used a method for emotional induction based on manipulated social feedback. Fundamentally, regardless of the chosen emotion induction method, it is a trade-off between ecological validity and experimental control (Levenson, 2003). Conservative procedures, such as watching video clips (Fakhrhosseini and Myounghoon, 2017), displaying powerful or amusing photos or listening to music, do not entail personal implications. For this reason, we assessed that those methods are suboptimal for our experiment, which concerns the manifestations of emotion in movement and cardiac signals. There are other methods to induce emotions such as autobiographic recall, also known as relived emotions, imagery of specific events and situational procedures such as adapting certain facial expressions to evoke a particular emotion, changing the environmental conditions such as heating the room to an uncomfortable temperature to induce anger, or to provide an enjoyable gift to induce happiness (Siedlecka and Denson, 2019). Deception studies, such as Harmon-Jones and Sigelman's (2001) work on anger and aggression, arguably provide the closest to a real-life type of emotional induction in laboratory settings. The approach we have used in our study that affords high ecological validity relies on deception, based on success-failure manipulations owing to the personal involvement of participants in the process (Nummenmaa and Niemi, 2004), coupled with a picture type of emotion induction.

In this approach, each participant's performance is subjectively evaluated by other members and followed by the presentation of a manipulated (in predetermined order) feedback of being perceived as the best, a tie, or the worst. The feedback is directed explicitly at the individual and their efforts, making the induction more personal. On top of that, if the task based on which the person receives feedback is of personal value, then the induction is expected to generate even a greater effect.

In summary, the original contribution of the present research is an experimental paradigm for studying the natural

interplay between synchrony and emotion (positive, neutral, and negative), in the different modalities of behavioural, psychological, and physiological modalities, based on a new analytical tool for adjusting raw, three-dimensional and non-stationary signals to extract phase synchronisation. Specifically, we used a social feedback emotion induction technique based on a personally relevant task. Moreover, we developed an experimental paradigm in which participants explored space in three dimensions (instead of one or two) and suggested a five-step process to analyse group synchronisation for $N > 2$.

Materials and methods

Participants

Thirty-nine adults (21 females, mean age = 25.4 years, SD = 5.7) participated in the study. Participants were volunteers (authors' network and students from various universities in Montpellier) who self-reported enjoying dancing as their leisure pastime or were professional dancers. Thirty-six were right-handed, and three were ambidextrous and obtained an Edinburgh Handedness Questionnaire (EHQ) score >-50. All participants were naïve to the goal of the study. They reported having no physical disabilities of any kind and had normal or corrected-to-normal vision. They did not benefit from any financial or material indemnity and participated with the goal of the advancement of scientific knowledge.

Participants were organised into groups of three people (triads) to perform the task together. These triads were randomly generated in groups of same-sex participants with no prior acquaintances within either of the group members. Most participants (N = 33) had no prior improvisational (e.g., dancing, gymnastics) experience other than leisure pastime, and six participants had intermediate experience with occasional group performances.

Before the start of the experiment, all participants read the information letter and gave written informed consent. The Institutional Review Board (IRB #2002A) approved the research protocol of the EuroMov Digital Health in Motion research unit, Montpellier, France.

Experimental setup

The experiment was held in the Motion Capture laboratory of EuroMov. Calibration and data acquisition were performed with the closed shutters daily before the experimental sessions. Body kinematics were recorded with the Vicon motion capture system (Nexus MX13 Vicon System), with eight infrared cameras and a sampling frequency set at 100 Hz. In the experiment, we used nine retroreflective markers placed on each participant, but in the light of the research question addressed in the present article, we used only three markers: right forehead (RFHD), left forehead (LFHD), and right head of the second metacarpal bone (RFIN), providing global information about hand movement. Those body points were selected during pilot runs as meaningful for extracting the participants' body kinematics for the computation of group synchronisation. In addition, we captured participants' cardiac activity *via* the Delsys Trigno wireless biofeedback system with Avanti EKG sensors (placed according to Delsys guidelines). The sampling frequency of cardiac data acquisition was set to 2,148 Hz, with recordings being triggered by the analogue board of the Vicon System to synchronise temporal data alignment. We used the Delsys Trigno Research + system for synchronous recordings of multiple devices. The Vicon system was connected to the Delsys system *via* the Vicon analogue board and a Delsys trigger box. The Delsys System was launched once from the beginning until the end of the experiment. Each time a Vicon recording was launched, the Delsys trigger generated an electrical spike to start acquiring ECG data and dropped to baseline level when the recording stopped. Afterward, these spikes in activity were used to identify the start and end of the trial. The Delsys ECG electrode signal and the Vicon motion capture data were automatically aligned regarding time stamps *via* the Vicon analogue board. Mobile devices were not connected to the Delsys as they were controlled from the Mentimeter website[1] and launched manually for all the participants at the exact moment. We developed a Python code to change the slides simultaneously. For this, we needed to keep the different Mentimeter presentations for each of the participants on separate tabs within a browser. With each click of the letter R, a series of commands were generated: Ctrl 1 (to open the first tab), then right arrow (to go to the next slide), then Ctrl 2, then right arrow, then Ctrl 3 and right arrow.

Before each experiment, the participant number was attributed to each individual in order to anonymise their data for processing. Participants were invited to stand in the part of the triangle in all trials, on a demarcated space for each participant (1.2 m distance in a straight line from each other), with the right hand slightly extended toward the centre of the formed equilateral triangle (angles 60° each). Participants were also asked to charge and bring their phones to the experiment to be used for the emotional induction procedure.

Experimental task

The current experiment was developed based on the mirror game paradigm for dyadic interaction (Noy et al., 2011) and extended to a group interaction (Himberg et al., 2018). Importantly, in our experiment (**Figure 1**), no specific instruction to synchronise was provided. This was to attribute the rise in synchronisation level to spontaneous entrainment

1 mentimeter.com

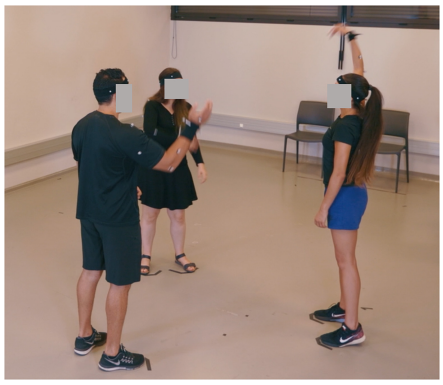


FIGURE 1
Experimental setup with three participants engaged in the movement improvisation task.

between participants. However, during the trial, we kept the original, explicit instruction used in the modified mirror game task to create complex, varied and interesting movements with the right hand. Additionally, we instructed participants not to communicate during the experiment. Finally, participants were asked not to move their feet and only to express themselves with the movements of their right hand.

Experimental procedure

Before coming to the laboratory, the participants received general information about the experiment. To them, the experiment was about personality extraction from movement and the development of group synergies in dancing. Upon arrival at the laboratory and after giving their written informed consent, they were equipped with the motion capture markers and instructed on how to place the Delsys Trigno ECG sensor correctly. Next, the accuracy of the recorded ECG data and specifically a salient QRS complex was verified visually before the experiment's launch. There were 15 trials of 30 s each (7 min and 30 s in total). The order of trials was randomised and counterbalanced across groups. Specifically, two random orders of trials were generated; seven triads were induced accordingly to the first order and six triads were induced accordingly to the second order. Jumping or turning around during the trials was not allowed.

After each trial, participants were asked to rank the performance of each triad member (including themselves) for that particular trial. When all scores were submitted, each participant would receive a (pre-programmed) feedback score for their own performance coming from their triad mates. This feedback based on the group evaluation of one's performance was part of the emotion induction method. The detailed emotion induction method, cover story, and rationale are described in section "Emotion elicitation". Following each trial, all three participants received the same feedback (i.e., all positive, neutral, or negative). Participants could not see the others' scores and thus were unaware that the (pre-programmed) results were the same for everyone.

After each emotion induction, we sought to detect resulted changes in the following trial. A particular case was the first trial which was not included in the analysis because there was no emotion induction before it. As of the second trial, the participants began to evaluate each other's performance in the preceding trial and received an emotion induction followed by a trial that uncovered the induction effect.

The ranking was performed using the participants' own phones connected to menti.com. Mentimeter is a website designed for interactive presentations but was precisely adjusted here by the experimenter for emotion elicitation. Once connected to the Mentimeter presentation, the computer screen was shown to illustrate the outcome of the triad vote (**Figure 2**). Before starting the experiment, participants were asked to answer the questions *via* menti.com and familiarise themselves with the process of answering them on their smartphones.

When feedback was submitted, three more questions were prompted on a screen to evaluate two emotion scales—pleasure and arousal—and their social consequences (see **Figure 3**). The first two questions were the scales of affective dimensions derived from the Self-Assessment Manikin (Bradley and Lang, 1994) on valence (**Figure 3A**) and arousal (**Figure 3B**) for assessment of the emotion associated with the participants' performance and the manipulated feedback they received. The third question (**Figure 3C**) assessed the social consequences of the preceding emotional elicitation. In part, it contains the motivational aspect of the individual to perform the task. For this article, the participants' Mentimeter is presented in English, whilst participants received their feedback in French.

Then, the experimenter discussed with participants their impression of the experiment to verify whether anyone understood that obtained feedback was manipulated. Finally, the deception procedure for emotion elicitation of the study was uncovered for participants, as well as the necessity of such a deception design.

Emotion elicitation

All participants were subjected to a social deception procedure with a cover story presented before the launch of the experiment that all participants in the triad would be asked to provide rankings of the performance of their triad mates and receive one themselves, based on the esthetical value and complexity of their movements. Being ranked "the best" provides three points, "second" two points and "third" one point. In such a manner, the range of possible points was between three (everyone ranked a person as the worst) and nine (everyone ranked a person as the best). The cumulative score



FIGURE 2
The first screen was visible before the experiment started to explain to the participants how the feedback worked, first before the votes **(A)**, then after the polls **(B)**, with the possibility that sometimes the scores could be tied **(C)**.

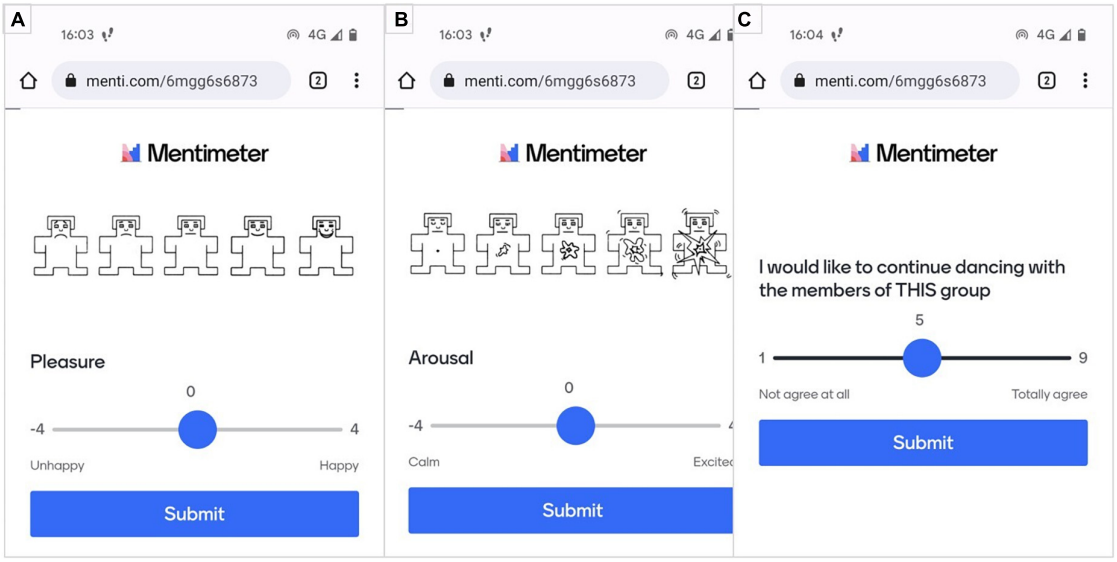


FIGURE 3
Evaluation of emotional [**(A)** pleasure; **(B)** arousal] and social **(C)** consequences after each performed trial.

of rankings of three participants was said to be automatically calculated and then provided personally to each individual.

As stated in the introduction, the emotion induction method is a compromise between ecological validity and experimental control, and we discuss the two aspects. Firstly, for the induction method to have high ecological validity, the goal is to create an elicitation environment in which the induction is personally relevant. For this reason, the task in which the participants are engaged must be of importance to them. Our experimental task is based on expressive improvisation dancing. The emotional induction was achieved through feedback concerning perceived dancing performance. The feedback starts with the participant's name to render the evaluation person-oriented. Specifically, after each trial, the participants received personalised positive or negative feedback: "Name, you are the BEST" (**Figure 4A**) and "Name, you were chosen the WORST" (**Figure 4C**). Receiving evaluative feedback from competent peers of being chosen as "the best" in a personally valuable task (i.e., dancing for dancers) would result in a more positive affect. Conversely, being selected as "the worst" would result in a more negative affect. Moreover, to enhance the feedback's evaluative form and facilitate interpretation by making the evaluation more salient, the words "BEST" and "WORST" were in capital letters. In addition, to reinforce the induction, we used images from the Open Affective Standardized Image Set (OASIS) (Kurdi et al., 2017) of the same arousal level but opposite valence level. In this way, the positive visual stimulus (e.g., fireworks) has a valence score of 6.27 and arousal of 4.98; the negative stimulus, e.g., parts of a house on fire, has a valence score of 1.73 and arousal of 5.28.

The control condition was used as a baseline. We opted for feedback that contained uncertainty for the participants: They would receive the feedback "You are tied (best or worst) or in 2nd place" (**Figure 4B**). We expected that this ambiguity of possibly being the best and the worst simultaneously would result in a more neutral induction.

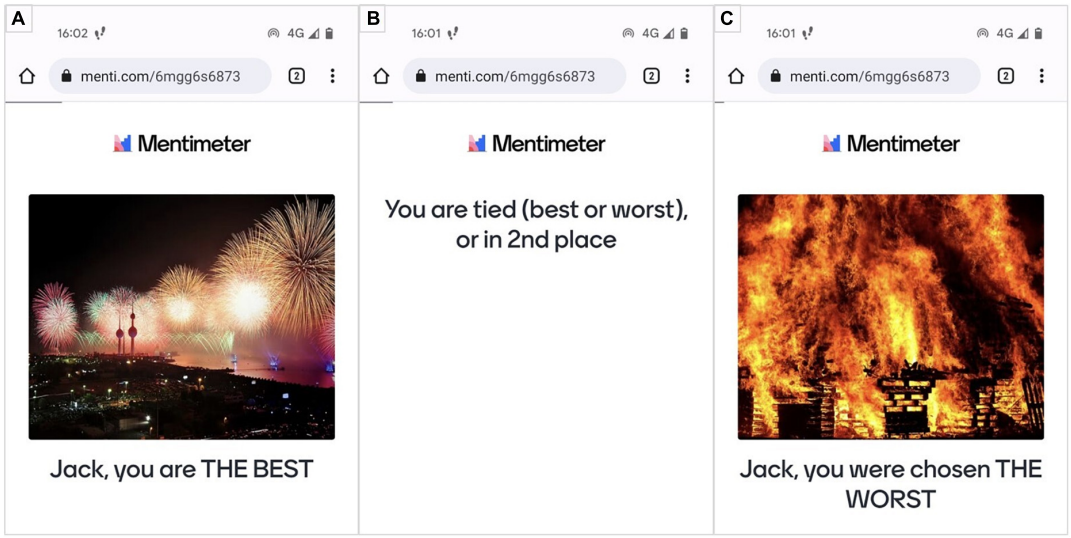


FIGURE 4
Emotion induction with positive feedback and positively valenced image from the OASIS database **(A)**, neutral state **(B)**, and negative emotion induction with negatively valenced image from the OASIS database **(C)**.

Variables, data processing, and statistics

For our independent variable, there were three experimental conditions for eliciting emotions (within-subject factor): positive emotion (P), neutral state (Nt), and negative emotion (Ng). The stimulus was the feedback received on the smartphones about the ranking score. This score was manipulated, and everyone in the triad received *de facto* the same feedback.

For our dependent variables, three modalities were analysed: behavioural [i.e., Time-in-Synchrony (TIS) scores of velocities], psychological (i.e., Self-Assessment Manikin (SAM) scale (Pleasure, Arousal) and Social Consequences scores), and physiological (i.e., TIS of time series of intervals between two successive heartbeats called the RR interval).

Behavioural data

The three-dimensional coordinates of hand movements were acquired. The hand was decided to be used as a reference point because the task consisted of hand movements, and the information provided by the cinematics of the hand marker was enough to extract the movement richness in the improvisational task. Then, the data were inspected and labelled. Data inspection was performed with the software Vicon Nexus 1.8.5. The labelling of each of three retro-reflective markers (one on hand and two on the head) was performed manually. If the gaps in trajectories were identified, the built-in gap-filling spline function was used.

Several mid-layer variables were calculated from these raw data: coordinate velocities, accelerations, and angles of head markers, which were later used to compute our metrics.

Velocity calculation

The total velocity is the norm of the coordinate velocity vector that is if we note by $P(t) = [x(t), y(t), z(t)]$ the position of a marker at the time t, then the coordinate velocities are

$$\left[\frac{dx}{dt}, \frac{dy}{dt}, \frac{dz}{dt}\right] \text{ and total velocity}$$

$$v(t) = \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2 + \left(\frac{dz}{dt}\right)^2}$$

The issue with raw velocities is that the anthropometric data influence their calculation. Therefore, we normalised the data before metric calculation. In this experiment, the participants formed a triangle. Each triangle angle was indicated with a special spot on the ground of the laboratory, indicating a specific place for participant one, two and three. Each participant was always occupying the same physical place in all trials. We used three reflective markers placed on the floor, one for each participant, before the start of data acquisition. By keeping the setup consistent across different triads, we were able to use the position of three markers placed on the ground as reference points for the local coordinates of three participants. Then, for each participant, we shifted and rotated each of them to a particular point in space. Then their limb movements were normalised. The maximal distance between the head and hand marker was calculated for each person. Then all position data were multiplied in order to bring this maximal distance to the

same value for all three participants. This allowed neglecting the anthropometric differences between individuals.

Firstly, the original velocities (Figure 5A) were extracted for each trial. Secondly, local detrending was performed to detect the oscillations by bringing the inflexion points to 0. When we compare the velocity variation between individuals, it is not the amplitude of that variation that counts but the oscillatory part. In simpler terms, a large movement of a particular oscillation would be similar to a small movement of the same oscillations. In order to extract the oscillatory part of the movement, we were inspired by the detrending techniques that we adapted to local levels. Schematically, for a given signal $s(t)$ we first calculate the inflection points $(t(k), s(t(k))$ that is such as $s''(t(k)) = 0$. In other words, we detect instances where a second derivative of the position time series equals 0. Then, we create a piecewise linear curve $L(t)$ by joining successive $(t(k), s(t(k))$ by linear interpolation. This permits calculating the detrended signal $S(t) = s(t) - L(t)$. This operation brings the inflexion points to 0 (Figure 5B).

The next step was to bring the local maxima of $S(t)$ to 1 and the local minima of $S(t)$ to -1. These successive new maxima and minima were connected by a local sine-like function (Figure 5C). The phases of these oscillatory signals were extracted with the Hilbert transform (Figure 5D). Finally, we calculated the Order Parameter of Kuramoto (Figure 5E), which quantifies the proximity of phases. Let $\theta_1(t)$, $\theta_2(t)$, $\theta_3(t)$ be the phases of 3 individuals at time t. The vectors $p_k(t) = exp\,(i \times \theta_k(t))\,,\ \ k = 1,\ 2,\ 3$ have modulus 1. The Order Parameter at time t is the modulus of the mean vector.

$$opmt\ (t) = \left| \frac{1}{3} \sum_{k=1}^{3} p_k\,(t) \right|$$

Our metrics of interest—time in synchrony (TIS)—were computed from the phase data. A significant duration threshold of 3 s (10% of trial duration) was used to consider that TIS were valid. Another important point is the thresholds of TIS values. We calculated the probability distribution of Order Parameter values for a given triad through all its trials. Then, the TIS of order parameter was extracted according to the IQR principle, where Q1 represented the lower threshold for the weak synchronisation (less than or equal to 75% of pdf data), Q2—medium synchronisation (50% of data), and Q3— strong synchronisation (25% of data). In this study, we analysed the three levels of synchronisation, and prioritising, however, the results obtained with the weak level. The first reason is based upon the exploratory nature of using the Kuramoto model for the identification of affective information. The second reason relates to the non-linear dynamics literature on human synchronisation, in which humans are often regarded as weakly coupled oscillators (Pikovsky et al., 2001) as opposed to mediumly coupled (e.g., humans with haptic contact such as walking hand in hand) or strongly coupled oscillators (e.g., car wheels connected by the car axle).

In order to verify whether the effect found was not due to chance, we randomly generated new fake triads, or

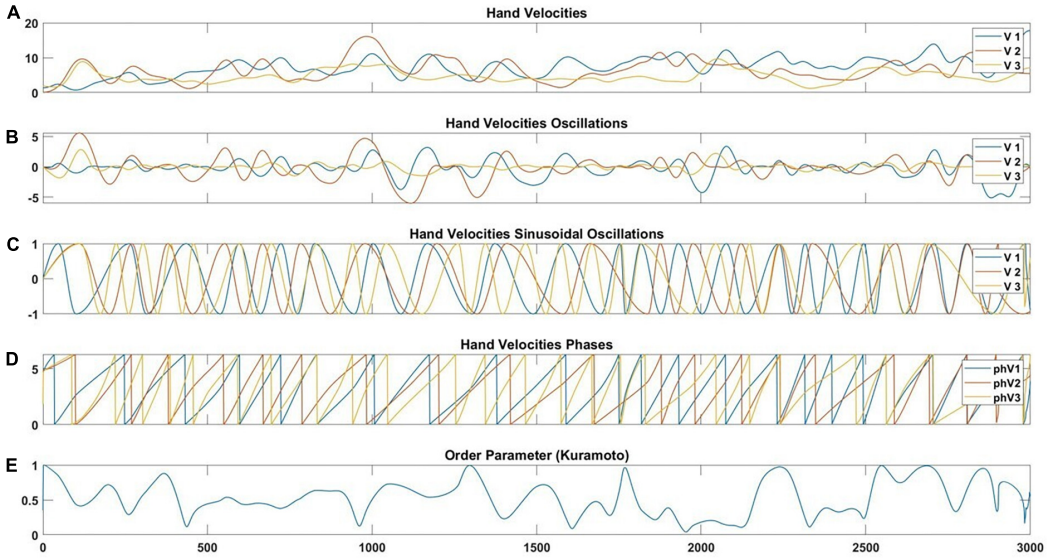


FIGURE 5
Illustration of the velocity pre-processing steps. Taking the raw signal **(A)**, implementing local detrending **(B)**, and the undulatory part of the signal **(C)** are used to extract phases with the Hilbert Transform **(D)** and implementation of the Kuramoto order parameter **(E)**. Within the graph legend, the V1, V2, and V3 correspond to the velocity of participant 1 (V1), participant 2 (V2), and participant 3 (V3). In addition, the phV1, phV2, and phV3 correspond to the we extracted phase velocities of participant 1 (phV1), participant 2 (phV2), and participant 3 (phV3).

pseudogroups, and compared them with the experimentally obtained data. Pseudo groups were organised by shuffling velocity time series from all triads and all trials and then randomly pairing them. For instance, one pseudo trial could be organised by pairing velocity time series from Participant (1) Triad (1) Trial (1) with Participant (3) Triad (11) Trial (9) and Participant (3) Triad (4) Trial (15). Afterwards, the other velocity time series were shuffled and paired until all the pseudo trials were generated.

Finally, to control that the task was executed correctly and that the participants were paying attention to each other, we dynamically built a triangle out of the head data for each individual. First, the centre point between each pair of LFHD and RFHD was found. The left-head to right-head points define a parallel to face vector f. Then a perpendicular vector to f was derived to detect the facing direction (head orientation). For each pair of participants (i, j) there were two numbers extracted. Pair i-j means participant i is facing participant j and pair j-i means that participant j is facing participant i. There were six pairs of numbers, two for each participant (e.g., for participant one: pair 1-2 and pair 1-3). The angles were calculated for each participant's directedness into the triangle. For the clarity of calculation, the angles were transformed into percentages. For example, the value of 0.5 means that the head orientation was exactly in the centre of the triangle. For a dynamical triangle for this specific angle with an angle of 80°, the 0.5 value means that the facing angle is 40°. The closer the value is to 0 for one pair, the more this first participant orients their head toward the second person. If the value is 1 or above, it means that the person is looking at the opposite person or even further outside the triangle. Negative values are not possible. We arbitrarily chose the value of 0.6 as a threshold for head orientation inside the dynamical triangle.

Psychological data

To detect how successful was the induction, we used Self-Assessment Manikin (SAM) scale (Bradley and Lang, 1994). It is a graphical and non-verbal procedure that portrays human-like figures with different faces and sizes for two different scales: pleasure and arousal. For the valance scale, figures range from unhappy to happy and for the arousal scale, figures range from calm to excited. Participants were instructed to identify themselves corresponding to their place on the continuums. The values for both scales ranged from −4 to 4. In addition, given a number of outcomes to which leads synchronisation, we included a scale for social consequences to investigate the impact of emotional induction and movement in unison on the desire to be engaged with the same individuals in the same activity in the future. The question ranged from 1 to 9 and participants needed to choose a score corresponding to their desire at the moment of being engaged with the same individuals (see **Figure 3**).

Physiological data

We obtained the ECG data with wireless Trigno Avanti Delsys biosensors. Participants placed the electrodes on disinfected skin for better electrical connectivity using the Delsys manual in a modified 3-lead ECG configuration. Electrode V– was placed on the left side below pectoral muscles on the lower edge of the left rib cage. Electrode V+ electrode was placed on the right side below the pectoral muscles on the lower edge of the right rib cage. The sensor body was placed under the positive electrode. R waves are the highest peaks seen on the ECG making them the easiest waves to detect. To be able to analyse heart data, we implemented sym4 wavelet transform to identify the R waves within the QRS complex. Given that individuals vary with regard to their resistance to the current flow as well as slight differences in electrode placements, the obtained ECG signal was of varying amplitude between different people. This caused the peak height to vary between the individuals that do not allow a one-size-fits-all parameter (i.e., the height of the peak and the distance between two successive peaks). To deal with this, as well as with artefacts for pre-processing of the data, we followed a series of steps: firstly, we automatically implemented wavelet transform on all the trials on all the people automatically in a loop. Then, we identified the physiologically implausible values for a moving person with an additional margin (i.e., less than 60 bpm or more than 120 bpm). If the chosen amplitude threshold is too high for a given individual, that will cause not identified peaks leading to a strongly decreased bpm rate. If on the other side the chosen amplitude threshold is too low for a given individual, that would identify by mistake not only the R wave leading to a strongly increased bpm rate. Afterward, these peaks were manually adjusted for each 30-s trial for each individual and compared visually with the raw ECG signal to ensure the correct detection.

Once the R peaks were accurately detected, they were modified into millisecond intervals between two successive heartbeats (i.e., RR intervals). To prepare such a non-stationary signal for phase detection, we transformed the signal. We created a new time series where we allocated number 1 for the time points of identified peaks. Next, we identified the midpoints between each pair of two successive heartbeats and allocated the number −1. This allowed deriving a sinusoidal-like time-series signal prepared for the Hilbert transform implementation. While this transformation brings to the artificial +1 value the heart peaks, it keeps absolutely all information about heart beat intervals and variability identical. It has the advantage that the transformed signal can be processed with continuous signal processing tools (FFT analyses, Hilbert transform method) in order to extract the phase modulation, and allows to interpret results from different levels of analysis (e.g., behavioural, physiological) in the same "language."

Separate one-way repeated measure ANOVAs were run on each of the metrics of interest, with appropriate

post hoc comparisons to clarify significant differences between conditions. For this, we averaged different trial values per each emotion nested within each triad (i.e., an average of five trials for each of three emotional conditions). Statistical analyses were performed in the JASP software.

Results

Emotion effect on movement synchronisation

To investigate the impact of emotion, our independent variable, on spontaneous time spent in synchronisation, our dependent variable, we used the TIS metric of the *weak* level. This value was obtained per each trial as a cumulative score for the three participants. The possible range of values is between 0 s (e.g., no attained synchronisation) and 30 s (e.g., synchronisation during the whole duration of the trial). There was a statistically significant main effect of emotion on TIS behavioural scores suggesting that there was a difference between at least two experimental conditions, $F(2, 24) = 61.65$ ($p < 0.001$), $\eta_p^2 = 0.84$. The measures of central tendency and dispersion are as follows: negative emotion (mean = 19.84, SD = 0.41), neutral state (mean = 20.08, SD = 0.67) and positive emotion (mean = 22.28, SD = 0.54). *Post hoc* pairwise *t*-test comparisons with Bonferroni correction revealed that positive emotion was statistically significantly different from negative ($p_{bonf} < 0.001$, 95% CI = [−3.06, −1.82]) and neutral state ($p_{bonf} < 0.001$, 95% CI = [−2.81, −1.57]) no significant difference between negative emotion and neutral state ($p_{bonf} = 0.952$, 95% CI = [−0.87, 3.75]). This indicates that participants spontaneously spent more time in synchrony when they were positively emotionally induced (**Figure 6**). The effect was non-significant for medium level of TIS $F(2, 24) = 3.27$ ($p = 0.055$), $\eta_p^2 = 0.21$ and remained significant for high level of TIS $F(2, 24) = 5.87$ ($p = 0.008$), $\eta_p^2 = 0.33$.

To test whether this result was due to chance, we carried out pseudo synchrony measures. This approach consists of random reorganisation of individual trials from different triads and computing of the TIS scores. This pseudo behavioural synchrony measure was not significant for any pair of emotions [$F(2, 24) = 0.14$ ($p = 0.870$), $\eta_p^2 = 0.01$], suggesting that the effects of emotion on movement behaviour are not due to chance. With respect to controlling the head orientation, we have arbitrarily chosen a threshold of 0.6 of the values within the dynamic triangle, and we obtained less than 15% of data points larger than the threshold. Given the approximative nature of the threshold, this amount of data is inconsequential and therefore we can conclude that participants complied with the instructions for executing the task and were paying attention to each other.

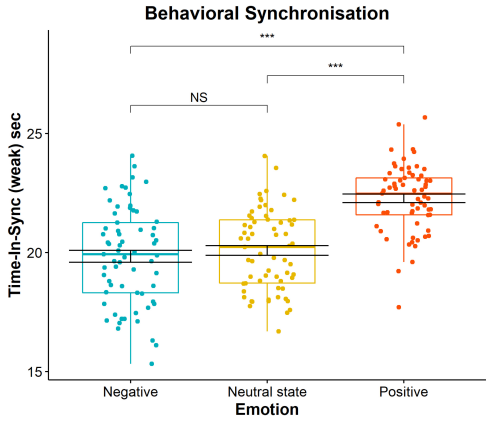


FIGURE 6
Time in synchrony (s) pairwise comparison for each of the three emotional conditions (negative emotion, neutral state, and positive emotions). Each dot represents a score of one 30 s trial. Significance levels 0.001, 0.01, or 0.05 are indicated with *, **, and *, respectively.

Emotion effect on pleasure, arousal, and social consequences

Right after every emotional induction and before the execution of the movement in the next trial, participants reported scores on the Self-Assessment Manikin (SAM) scale. There were two 9-item scales, pleasure and arousal, ranging from −4 to 4. In addition, there was a social consequence on 9 item scale ranging from 1 to 9. The scores for the SAM questionnaire as well as the social consequences item are the dependent variables.

For the SAM pleasure score, there was a statistically significant main effect of emotion on SAM pleasure scores suggesting that there were differences between at least two experimental conditions [$F(2, 24) = 3.85$, $p = 0.035$, $\eta_p^2 = 0.24$]. The measures of central tendency and dispersion are as follows: negative emotion (mean = 1.75, SD = 1.17), neutral state (mean = 2.05, SD = 0.85) and positive emotion (mean = 2.22, SD = 0.86). *Post hoc* pairwise *t*-test comparison revealed significant difference only between negative and positive emotional conditions ($p_{bonf} = 0.034$, 95% CI = [−0.92, −0.03]) but not negative and neutral ($p_{bonf} = 0.282$, 95% CI = [−0.75, 0.14]) nor neutral and positive ($p_{bonf} = 0.982$, 95% CI = [−0.62, 0.27]). The results indicate that positive emotional induction generated perceived higher valence scores and negative emotional induction caused a decline and lowered valence score.

For the SAM arousal scores, the sphericity assumption was violated and therefore the Greenhouse-Geisser correction was implemented. There was no statistically significant difference [$F(1.38, 16.76) = 2.80$, $p = 0.103$, $\eta_p^2 = 0.19$].

For the social consequences scores, there was a statistically significant main effect indicating that there was a difference between at least two experimental conditions [$F(2, 24) = 13.95$, $p < 0.001$, $\eta_p^2 = 0.54$]. The measures of central tendency and dispersion are as follows: negative emotion (mean = 6.28, SD = 1.54), neutral state (mean = 6.64, SD = 1.34) and positive emotion (mean = 6.90, SD = 1.30). *Post hoc* pairwise *t*-test comparisons were significant for negative and neutral ($p_{bonf} = 0.017$, 95% CI = [−0.66, −0.05]) and negative and positive ($p_{bonf} < 0.001$, 95% CI = [−0.92, −0.32]) but was not different between neutral and positive inductions ($p_{bonf} = 0.105$, 95% CI = [−0.56, −0.04]). Negative emotion had the weakest social consequences and positive having the strongest ones.

Emotion effect on physiology

We transformed the raw inter-beat interval time series into an oscillatory-like time series. This allowed the implementation of Kuramoto analysis and specifically the time series of the order parameter TIS, the dependent variable, per each executed trial as a function of induced emotion, the independent variable. The main effect of emotion on the physiological rhythm entrainment (dependent variable is TIS scores of RR intervals) was also investigated using the one-way repeated measures ANOVA. The results were not significant [$F(2, 24) = 0.53$, $p = 0.594$, $\eta_p^2 = 0.04$]. The effect was neither significant for medium level of TIS [$F(2, 24) = 1.14$, $p = 0.336$, $\eta_p^2 = 0.09$] nor for the high level of TIS [$F(2, 24) = 0.57$, $p = 0.576$, $\eta_p^2 = 0.05$].

Discussion

The aim of the present study was to investigate the effect of naturalistically induced emotion on synchronisation occurring across behavioural, psychological, and physiological modalities, with positive emotion expected to facilitated the beat in unison between interactants and negative emotion to disrupt it.

Behavioural modality

We confirmed our hypothesis that individuals induced with positive emotion would spend more time in spontaneous synchronisation than when they were induced with a neutral state and negative emotion conditions. Nevertheless, the negative emotion was not significantly different from the neutral state. These results confirm earlier findings (for instance, Tschacher et al., 2014) and suggest that positive affect is positively correlated to interpersonal movement synchronisation. At the same time, the observed asymmetry between positive and negative inductions contradicts the well-established negativity bias in psychological research (Rozin and Royzman, 2001) that humans are more efficiently induced by negative emotions than by positive ones. It is possible that moving together and just the mere sharing of a physical space facilitate interaction and help people bind together. Presumably, the improvisational type of interaction affords individuals with a drive towards social "likes" to develop strong social ties. There were no significant differences in TIS scores between negative emotion and neutral state. In fact, we have built the neutral condition in such a way that the ambiguity of possibly being the best and the worst at the same time would result in a more neutral induction. It is possible that this would have induced a positive valence in some participants and negative valence in others. However, as differences were found between neutral and non-neutral conditions for some variables (for instance, the social consequence score, see below), this possibility is not entirely convincing.

Psychological modality

We obtained a significant effect of emotion on pleasure scores but not arousal scores. As mentioned in the introduction, human emotions are not just changes in valence (pleasure scale) but involve a delicate combination between valence, arousal, behaviour and physiology. Given that there were emotional effects not only at the behavioural modality but also at the psychological level, we can conclude that the emotion induction was successful. As for the social consequences, the positive induction increased personal will to engage in a task with the same group members and this was decreased with the negative induction. This is rather a straightforward finding, as it suggests that our social consequences variable can determine the potential benefits of synchrony. What is not yet clear is whether this effect is due to emotional induction, movement synchrony, or both. This is important because it can be used as a tool for developing synergies and strengthening the cohesion levels of a group to attain higher performances.

Physiological modality

We did not find any significant main effect of emotions on the cardiac activity of the triad. What can be the reason(s) for the absence of an experimental effect on the physiological synchrony, an effect that was found before (e.g., Konvalinka et al., 2011)? One reason may relate to the different metrics used in different studies. For instance, Konvalinka et al. (2011) used a recurrence quantification analysis on cardiac activity, whereas we transformed the signal into a sinusoidal-like signal

in order to homogenise our analyses between behavioural and physiological modalities. Another reason relates to the possible impact of physical activity on the Autonomic Nervous System (ANS), which is perhaps larger than the impact of emotion on ANS and could have dominated it. The possible solution is to adapt the task and adopt one that would reduce the movement components to their minimum.

Conclusion, limitations, and future work

From a theoretical standpoint, this study contributes to verifying whether ecological emotion elicitation can be manifested in human movement and interpersonal motor synchrony and provides a fundamental understanding of how different affective states result in human group synchronisation. From an applied perspective, these results can be used in the rehabilitation context, in which, based on the patient's movement, synchrony-based recovery interventions can be used to develop rapport (Fuchs and Koch, 2014) and facilitate, for instance, Autism Spectrum Disorder adaptations (Manders et al., 2021). They can also be used to improve human-machine interactions, for example, in adjusting behavioural interactions with human individuals based on their affective state and creating synergies within the group.

One limitation of our study is the possible blending of the effect of two different emotional induction procedures (i.e., deception based on social comparison and affective picture dataset). We cannot completely separate the part of emotion induction that relates to the naturalistic scenario of being evaluated in a personally valuable task by others and the part of emotion induction coming from emotionally inducing pictures. For this reason, a separate study might test each induction method in isolation and then together, preferably within a repeated-measures design to reduce the inter-individual differences. The goal of the present study was not to validate a specific and unique method of induction but rather to attain a high induction efficiency. In this light, the choice of reinforcing manipulated social feedback with an intuitive and fast mean appears justified. In post-experimental debrief, spontaneous feedback provided by a few participants was that they understood immediately from the pictures, without reading the text, whether they were getting a positive or a negative result. In such a manner, it seems that the pictures cued some participants to a specific emotion and helped make the induction instantaneous.

Another limitation of our study is the potential entanglement between emotion and motivation for the chosen experimental task. Indeed, after receiving evaluative social feedback with respect to their own performance, participants could have been more motivated in doing the task, creating a potential confound between emotion and motivation. Against this interpretation are the facts that emotion and motivation are not entirely stackable—the same negative emotion induction for the same individual can arouse anger and increased motivation on one occasion, and can cause sadness and decreased motivation on another occasion—and that a negative induction would have produced an increase in synchronisation, a result that was not found. More, we did tangentially control for the participants' motivation in our experiment, with the third question asked after each trial "Would you like to continue dancing with the members of this group?" We argue that this question embraces the motivation of individuals to engage in the task by exploring the fluctuations after each emotional induction. Answers to this question were significantly different between emotion conditions (i.e., lowest—negative, middle—neutral state, and highest—positive). Emotion is an emergent phenomenon that builds on motivation, and it is hard to separate them clearly. Emotions are intrinsic in individuals' achievement patterns (Nicholls, 1984; Dweck, 1986) and are approached as action tendencies (Frijda, 2007), suggesting that each experienced emotion guides and motivates individuals to engage in a specific action (e.g., anger to fight or fear to flight).

Due to the low sample size, care should be taken in generalising the presented findings. In addition, it is possible that emotional induction did not affect all triads and participants in the same way. Nevertheless, our statistical results related to the effect of emotion on behavioural TIS are strong (**Figure 6** demonstrates clustering of all data around mean values), indicating that despite interpersonal variability, there was a common and shared tendency toward spontaneous synchronisation.

This research focused on behaviour that combines naturalistic emotion induction and improvisational movements, with a trade-off between ecological validity of emotion induction and experimental control. This highlights the cardinal importance of selecting the best possible trade-off: Ecological validity shall not be sacrificed for the sake of high requirements for experimental control.

In future research, approaching emotion within a repeated-measures design seems a good strategy to be particularly cautious with the emotional aftereffects (Halovic et al., 2020), especially paying attention to the effect of emotions that can build up over time. Notably, emotions are non-linear in nature, meaning that one stimulus does not produce the same reaction between different individuals and even within the same individual on different occasions. Moreover, emotional induction is complicated for the repetitive type of experimental paradigms owing to a gradual individual's sensitisation to the same stimuli. This formulates a prominent line of research for mutually adapting human-computer and human-robot interaction systems that are occasion sensible and adjustable.

Another avenue when quantifying joint action in general, and synchronisation in particular, is to investigate different

emotion entanglement in interpersonal adaptations (Burgoon et al., 1995; Hart et al., 2014). For instance, how much the interaction shapes the individual's behaviour reflects the degree of behavioural change, which could be informative for illustrating the strength of interaction as a function of emotion. Additionally, the direction of change, or its absence, could reflect leadership processes within group dynamics and whether some emotions overpower others when there are more representatives with one particular emotion rather than another.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://osf.io/d45t3/.

Ethics statement

The studies involving human participants were reviewed and approved by IRB 2002A of the EuroMov Digital Health in Motion. The patients/participants provided their written informed consent to participate in this study.

Author contributions

AS conceived the idea of the manuscript with the help of MB, SJ, and BB, collected the data with the assistance of SP, analysed the data under the supervision of SJ and BB, and wrote the first draft of the manuscript. MB, SJ, and BB contributed to manuscript revision, and read and approved the submitted version. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Summary of Chapter 7

The second publication shed light on the effects of emotion induction on group sensorimotor synchronization in an unstructured experimental context. Although the participants were not given instruction to synchronize, we found that the participants spontaneously synchronized their movements for a longer time (i.e. Time-In-Sync metric) after positive emotion induction than after negative emotion and neutral state. After detecting a significant effect of interpersonal synchronization, it is necessary to perform a pseudosynchrony check. To this end, we shuffled the individual time series between different trials in each group, and the data showed that the observed behavioral synchronization was not spurious.

We tested a new method of emotion induction that provides both high ecological validity and high experimental control. In the context of a personally meaningful task for participants and subsequent personalized feedback, an emotion induction procedure based on the experimental manipulation of success and failure using performance feedback proved to be a valuable instrument.

In this study, the approach consisted in combining behavioral, psychological, and physiological modalities. We observed marked differences across behavioral and psychological subsystems in which positive emotion induction resulted in enhanced synchronization and valence scores. However, we did not find discernable effects of systemically induced emotions on interpersonal cardiac activity. Since the participants were standing and moving during the trials, it is possible that the movement led to large adjustments in the autonomic nervous system and suppressed the effect of emotions.

CHAPTER 9

Theme 3: Experimental 2.0

This chapter presents Publication № 3: **Smykovskyi**, A., Janaqi, S., Pla, S., Pierre, J., Bieńkiewicz, M. M. N., and Bardy, B. G. (2023). Negative Emotions Disrupt Intentional Synchronization during Group Sensorimotor Interaction. *Emotion*. *In press*.

The third publication (i.e., the second under the experimental theme) was devoted to investigating the effects of emotion on interpersonal synchronization in a more controlled and structured experimental setting. Specifically, three participants were seated around a table, and the task was performed without the involvement of gross muscular movements by intentionally synchronizing vertical oscillations of only the participant's index fingers. The existence of a significant relationship between the manipulated variables would corroborate whether the effect of emotion on behavior is robust even in the context of minimal freedom of action.

The task was characterized by little personal significance for individuals. The success of emotion induction would indicate that feedback based on social comparison is effective in contexts of low importance, and not only in contexts of higher value for self-identification (i.e., feedback on dancing performance for dancers).

In addition, the implication of gross motor skills that require the involvement of large body muscles was downsized to a minimum. Indeed, three participants sat around a table, performed oscillatory movements along the vertical axis with only their index finger, and were asked to synchronize their movements. The significant results in interpersonal cardiac activity would confirm that the lack of the effect in an unstructured task was a consequence of the gross muscle movements that absorbed and prevailed over the effect of emotion.

The *Emotion* journal was chosen for this publication. The aim of the journal includes publishing significant empirical contributions to the study of emotion through social, biological, and cognitive variables that push forward theories and knowledge regarding emotional processes (Journal scope statement). Our second experiment aims to investigate the influence of social and cognitive variables on emotional functioning.

Negative Emotions Disrupt Intentional Synchronization During Group Sensorimotor Interaction

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ABSTRACT

Emotions play a fundamental role in human interactions and trigger responses in physiological, psychological, and behavioral modalities. Interpersonal coordination often entails attunement between individuals in various modalities. Previous research has elucidated the mechanisms of interpersonal synchronization and the emotions aroused by joint action: cardiac activity aligns in disputing marital couples, spectators share enjoyment in observing live dance performances, and joint finger-tapping evokes positive emotions. However, little is known about the impact of emotions on intentional interpersonal synchronization. To address this problem, we conducted an experiment during 2022 asking 60 participants to engage in a three-way finger-tapping synchronization task. We systematically induced emotional states (positive, neutral, and negative) with social comparison feedback using success-failure manipulations. An analysis of behavior synchronization using the Kuramoto order parameter revealed that negative emotion induction significantly diminished time spent in synchrony compared to positive induction. Moreover, the

results exposed incremental struggles in attaining higher levels of synchronization (Q2-Q3) after the induction of negative emotions. These outcomes further substantiate the necessity of integrating the indices of agents' emotions into interpersonal synchronization and coordination models. We discuss the implications of this work for research on interpersonal emotion in joint action and applied outcomes in emotion-aware technologies and interventions.

KEYWORDS

Emotion, interpersonal synchronization, intentional synchronization, joint action, Kuramoto order parameter

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Introduction

In the course of biological and cultural evolution, emotions have become an instrument for social attunement. Negative emotions indicate animosity and lead to withdrawal from undesired interactions with extraneous groups (Rozin et al., 2009). In fact, the human brain is hardwired for the Us/Them dichotomy

(i.e., distinguishing between people of their kind and others), and negative emotions are fundamental in widening the gap between Us and Them (Sapolsky, 2017). There is some evidence that negative emotions can be beneficial. For instance, Lerner and Tiedens (2006) suggest that anger can facilitate decision-making to achieve desired outcomes by overcoming hesitation and over-analyzing. Moreover, people seek to increase anger as an instrumental emotion to improve individual performance in a confrontational context (Tamir et al., 2008). The key issue is that negative emotions are not inherently dysfunctional but can sometimes induce functional behaviors adapted to the specific context (Parrott, 2001). Positive emotions, in turn, act as a social glue. Adopting postures and behavior has the adaptive value of strengthening the affiliation with others, its allure, which ultimately leads to the improvement of evolutionary fitness (Lakin et al., 2003). Evolution reinforced congruent interpersonal behavior with pleasant sensations since imitating the movements of a person from the Us category activates the dopaminergic system (Losin et al., 2012). Considerable research efforts have been dedicated to investigating the influence of emotions on individual cognitive processes and behavioral responses.

However, emotions are triggered by an event in a person's environment, where interactions with other people play a key role. Some theoretical models are shifting the paradigm for emotion researchers from intraindividual study to an interpersonal realm. For instance, the Temporal Interpersonal Emotion Systems model (Butler, 2011) advocates that relationships between people operate as dynamic systems, characterized by a close interconnectedness of elements of the system, dependency on initial conditions and the system's past states, that all together give rise to an emergent property of self-organization, expressed in emotions that control the stabilization of behavior (i.e., morphostatis) or transition to another state (i.e., morphogenesis). Similarly, the Emotions as Social Information Model (van Kleef, 2009) puts forward expressions of emotions and subsequent appraisal processes in the form of inferences or affective reactions of the observer to explain how emotions regulate social interactions. In the model, social-relational (e.g., type of relationship, cultural norms, focus on a person or situation) and information-processing factors (e.g., cognitive implication) moderate the interpersonal effects of emotion. Finally, the Sociodynamic Model of Emotions (Mesquita & Boiger, 2014) postulates that social interactions and emotions represent an integral

and inseparable system. The model emphasizes that emotions do not exist a priori but rather emerge in interaction as functional and context-adapted constructs that form and shape interactions over time. The presented models illustrate the emerging trend toward the systematic study of emotions within interpersonal social dynamics, representing the "dark matter" of social neuroscience – not directly observable but an existing matter (Ayache et al., 2021; Schilbach et al., 2013). Our recent work (Bieńkiewicz et al., 2021) has shed light on the lacuna of empirical evidence on the effect of emotion on interpersonal rhythmic interactions in order to substantiate and enrich interpersonal emotion models.

Differentiating Emotion from Other Affective Constructs

Affect is an umbrella term encompassing various constructs such as emotion, feeling, and mood (Scherer, 2005). Russel and Barrett (1999) aptly drew an analogy by comparing the differentiation between emotion and other affective constructs to the parable of the blind men and an elephant. The analogy illustrates that the various affective constructs are merely different classes of events of the same underlying phenomenon. *Emotion* represents a multi-modal and multi-component process that entails a clear appraisal of an event that elicits a reaction of relatively short duration, triggering responses at behavioral, psychological, and physiological modalities (Sander et al., 2013). *Feeling*, on the other hand, is a single-component process that represents only the subjective experience of an emotional episode (Scherer, 2005). *Mood* does not have a clear antecedent, is less intense, and typically lasts longer than emotion (Beedie et al., 2005). And yet, all of the affective constructs discussed here[1] can be characterized in terms of valence.

Changes in valence serve as a necessary condition for changes in emotional states; however, changes in valence alone do not necessarily signify the emergence of an emotion (Quigley et al., 2014). Historically, the use of the word valence has been associated with the experience of positive or negative emotions that are

[1] It is important to acknowledge that these three constructs do not encompass the entirety of affect. In addition to mood, emotion, and feeling, there are other constructs to consider, including preferences, affect dispositions, interpersonal stances, temperament, and sentiments, among others.

inherently good or bad, leading to a "moralization of valence" (Colombetti, 2005). In fact, there are many dichotomies regarding how to classify positive and negative emotions, such as good-bad, right-wrong, pleasure-pain, approach-avoidance, and many others (Solomon & Stone, 2002). In this light, joy can be categorized as good, as right, or as one that brings pleasure, whereas anger can be categorized as bad, as wrong, and as one that causes pain. Each discrete emotion is characterized by a set of specific behavioral expressions. For instance, joy is often accompanied by smiling and laughter, while anger is commonly associated with furrowed brows and clenched fists. However, in contrast to this structuralist framework, we embrace here the functionalist perspective that views emotions as relevance detectors, guiding individual behaviors in the environment through strong action tendencies (Campos et al., 1989; Frijda et al., 2007; Sander et al., 2003). It is this distinguishing feature, along with the multi-modal and multi-component process, that sets emotions apart from other affective constructs.

Investigating the Influence of Emotions on Interpersonal Synchronization

Collective effervescence serves as a compelling example of the interplay between emotions and rhythmic joint action. Coined by Emile Durkheim (1995), collective effervescence describes the synchronization of intensities of individual emotional experiences resulting from participation in collective gatherings and rituals. Emotional contagion enables shared excitement in which people mimic and synchronize with other people's facial expressions, vocalizations, postures, and behavior (Hatfield et al., 1994). Importantly, mere sharing of physical space is not sufficient for the emergence of collective effervescence (Xygalatas et al., 2011), and personal involvement modifies the affective response (Fischer et al., 2014). For example, audience enjoyment of live dance performances in three out of four choreographic sessions was found to predict the perceived synchronization of performers' movements (Vicary et al., 2017). In a series of studies, Páez et al. (2015) empirically demonstrated the beneficial effect of collective effervescence on positive affect. Recently, Pizarro et al. (2022) conducted a meta-analysis of the influence of collective effervescence on, among others, emotions, and the authors further confirmed the beneficial effect on positive emotions. Nonetheless, the meta-analysis evidenced the absence of a meaningful influence of collective effervescence

on negative emotions. Important to note is that studies reviewed by Pizarro et al. (2022) did not experimentally manipulate collective gatherings in which negative emotions were induced.

One area of research that provides evidence of detrimental associations between synchronization and emotion is dyadic conversation and conflict. For example, Gates et al. (2015) established a positive association between respiratory sinus arrhythmia and the number of conflicts in marital couples. The mere act of conflict implicates the collision of opinions and reduces behavioral synchronization (Paxton & Dale, 2013). Although, behavioral attunement during conversations about recurrent disagreements in long-term married couples correlates with shared affect (Otero et al., 2020). Conceivably, the nature of the conversation influences interpersonal attunement. For instance, mutual regulation of cardiac activity emerges in romantic couples during social support discussions when one partner attempts to regulate emotions verbally by supporting another partner (Zee & Bolger, 2022).

To date, only a few studies have explicitly targeted the causal effects of emotions on between-person synchrony. Paxton and Dale (2013) examined the convergence of interpersonal behavior during dyadic conversations under two counterbalanced experimental conditions: an affiliative condition, in which participants discussed the media they liked, and an argumentative condition, in which participants discussed a topic on which they had strong but conflicting opinions and were instructed to persuade their interlocutor. The authors did not find conclusive evidence for the effect of emotions on behavioral convergence but acknowledged the necessity for further research. In their following study, Main et al. (2016) explored dyadic conflict interaction between mothers and adolescents, entailing a verbal confrontation over an intense topic of disagreement. Unlike the previous experiment, the authors did not systematically manipulate different emotional conditions but only explored negative emotion context (i.e., argument discussion). Human raters quantified positive, negative, and neutral emotional expressions using the Specific Affect Coding System during the interaction. The results demonstrated co-occurrence patterns between mothers and adolescents in both negative and positive displays, indicating emotional synchrony. By contrast, Tschacher et al. (2014) investigated five counterbalanced interactions: two conversations that promoted cooperation (i.e., developing a shared position and its justification to persuade an imaginary third person), two conversations

that stimulated competition (i.e., debates over arguments from the same list and debates where one participant gets a weak list of arguments and the other receives strong ones), and one fun task to create engaging and humorous atmosphere (i.e., composing a five-course meal consisting of meals and beverages that neither of the participants likes). The authors found positive associations between emotions and synchrony in dyadic conversations and used Granger causality to investigate the direction of the causal relationship between emotions and interpersonal synchrony. The results revealed the predominant effect of interpersonal synchrony on emotion rather than vice versa. Notwithstanding the evidence, the authors recognized that causality evaluation was limited to temporal inference and that future studies should induce emotions experimentally.

Balancing Ecological Validity and Challenges in Selecting Emotion Elicitation Methods

The three abovementioned studies used dyadic conversation as an experimental paradigm. However, as a method of inducing emotions, dyadic conversation suffers from low experimental control (Levenson, 2003). In general, the choice of the emotion induction method is "a frustrating trade-off between ecological validity and experimental control" (Levenson, 2003, p. 217). To overcome the problem of low experimental control, Fujiwara and Daibo (2018) systematically manipulated emotions using video clips that the authors preselected in a pilot study for the Japanese population. The results did not support the hypothesis of an effect of emotion as the precursor of synchronization. However, the emotion elucidation method can explain the absence of meaningful results. In fact, emotional video clips suffer from low ecological validity (Levenson, 2003). Standard methods of emotion elicitation (e.g., photos, music, and films) fail to induce emotions reliably across different people. Indeed, people vary in their sensitivity to different stimuli (Joseph et al., 2020). To illustrate, while for some people the image of a spider can be a highly arousing stimulus, for others, the spider is neutral. This poses a methodological challenge in finding a standardized and reliable emotion induction method.

Social psychological methods based on deception can effectively circumvent awareness bias and generate reliable emotional responses through psychological realism in the laboratory (Harmon-Jones et al., 2007). To remedy the problem of low ecological validity and low experimental control, we have recently developed an emotion induction procedure based on success-failure manipulations (Smykovskyi et al., 2022). In this type of induction, feedback on one's own success or failure and the person's participation in emotion-eliciting situations reinforce the emotional response (Nummenmaa & Niemi, 2004). Therefore, to enhance the personal relevance of the stimulus (to induce emotions), we incorporate individuals in the induction process and provide personalized performance feedback.

To increase standardization of the induction procedure among different people, we did not aim to induce any basic emotions, such as anger or sadness. In fact, after the same negative performance feedback, it is possible to induce anger in some participants as much as sadness in others. Moreover, Nummenmaa and Niemi (2004) warned that success-failure manipulations do not reliably target discrete emotions but instead produce discernible changes in the valence dimension of emotional states. For this reason, we decided to approach emotion elicitation in terms of different dimensions. Specifically, we expected that success manipulations would result in positive emotions and failure manipulations in negative emotions through changes in valence. Given the conceptualization of the emotion presented above, we adopt here a multimodal approach. Specifically, in addition to measuring behavioral (i.e., finger-tapping) and psychological responses to emotion induction, we examine a well-documented perspective of interpersonal cardiac activity (e.g., Gates et al., 2015; Konvalinka et al., 2011).

The Present Investigation

The results of our previous study (Smykovskyi et al., 2022) revealed that positive emotion induction fostered spontaneous synchronization and led to longer time maintained in synchronization (i.e., Time-In-Sync metric). It remains an open question whether the emotional effect can also be observed in an intentional synchronization scenario. Finger-tapping provides an appropriate experimental paradigm for

investigating intentional synchronization. While some studies assessed the effects of interpersonal finger tapping on emotional response (e.g., Rabinowitch & Cross, 2019; Zhang et al., 2016), the literature on the reciprocal effect is scarce. Addressing this issue is of pressing interest not only for fundamental science but also for human joint activity such as sports, military drills, and ensemble music performance, where intentionality underlies the ability to synchronize and generate potential positive consequences such as increased cohesion, empathy, and group efficacy.

Most interpersonal studies have examined dyadic social interaction while overlooking the emergent processes occurring at the group level (Dale et al., 2020). Namely, synchronization at the group level is not just the sum of its elements or the collection of pairwise relations. Instead, the group evolves, creating a "superorganism" that redefines the notion of an individual in the system and where the system becomes a new living entity (Emerson, 1939). In this context, a promising line of research is to identify the dynamics of entries and withdrawals from synchrony (e.g., Mayo & Gordon, 2020) and the process of coupling and uncoupling (e.g., Dumas & Fairhurst, 2021) that hints at group homology (i.e., how the geometry of group interaction - topology - changes over time) (Zhang et al., 2020). Moreover, the group-level analysis provides a framework for empirical research into the effect of collective effervescence and the group-related tasks that are otherwise not accessible at the dyad level (Keltner & Haidt, 1999). This rationale gives rise to a relatively new research trend of group synchronization (e.g., Bieńkiewicz et al., 2023; Dale et al., 2020; Fujiwara, 2016; Tomashin et al., 2022), which we follow in this manuscript.

Human interpersonal synchronization can be considered through the mathematical lens of coupled oscillators, which are pervasive in many biological and physical systems (Feldman, 2007; Helm et al., 2012; Nordham et al., 2018; Yokoyama & Yamamoto, 2011; Zee & Bolger, 2019). However, Strogatz (2003) highlighted three constraints in approaching synchronization between humans as the study of coupled oscillators. First, human interactions are rich and variable in frequencies, while the science of synchronization is constrained to repeating the same constant frequency. Second, people are more influenced by their physical neighbors–and perceptual interaction (Bardy et al., 2020)–while the science of synchronization is constrained to all-to-all topology in which coupling is usually equally strong and shared

between all oscillators simultaneously. Third, a reliable explanation of human behavior is challenging, while the science of synchronization requires a comprehensive explanation of the rules that govern interactions. Accordingly, an adaptation of the well-established Kuramoto model for human interaction has been proposed (Frank & Richardson, 2010; Richardson et al., 2012) and has been experimentally implemented using Time-In-Sync and Time-To-Sync metrics (Alderisio et al., 2017; Bardy et al., 2020; Calabrese et al., 2021; Smykovskyi et al., 2022). These metrics indicate the time spent in synchrony and the time needed to achieve the given synchronization level, respectively (see the Data Processing and Statistics subsection in the Methods section for details on synchronization analysis).

Hypotheses and Contributions

In line with previous research (Smykovskyi et al., 2022; Tschacher et al., 2014), the specific hypotheses of the present manuscript are that (1) the induction of negative emotions would result in lower synchronization scores than the neutral state (i.e., lower Time-In-Sync and higher Time-To-Sync metrics), (2) the induction of positive emotions would results in higher synchronization scores than the neutral state (i.e., higher Time-In-Sync and lower Time-To-Sync metrics). Finally, the main contributions of this manuscript are threefold:

- We propose a novel method of emotion elicitation based on success-failure manipulations using performance feedback and social comparison (see the Emotion Elicitation subsection in the Methods section).
- We demonstrate that the emotion induction method is effective even when the experimental task holds little personal significance (see the Emotion Induction Effect on Interpersonal Finger Synchronization subsection in the Results section).
- We illustrate how the nature of the data can determine the choice of the synchronization measurement method. We juxtapose the results of Kuramoto order parameter values for behavioral and physiological modalities (see the Emotion Induction Effect on Interpersonal Heart Synchronization subsection in the Results section).

Method

Participants

Sixty adult students from various universities in Montpellier (33 females, 27 males, M_{age} = 22.5 years, *SD* = 4.7, range = 18-39) participated in this study during 2022. They did not receive any benefit or form of financial or material compensation and reported no physical or mental disabilities.

We controlled for the rhythmic abilities and characterized participants' musical training in line with Rabinowitch and Cross's methodological approach (2019). A total of 39 people did not have any musical experience; 10 individuals played one musical instrument (singing included); 10 persons played two or more musical instruments, and one individual did not answer the question. Accordingly, no participants reported any difficulties in performing the rhythmical task.

Participants were randomly assigned into groups of three people (i.e., triads), and there were no prior acquaintances within either of the group members. Nine triads included only females, seven triads were composed of males, and four triads were mixed.

Before the start of the experiment, all participants read the information letter and provided written informed consent. The experimental procedure was approved by the local research ethics committee (N° IRB-EM: 2106D).

Experimental Setup

The experiment was held in the Huyghens laboratory of the EuroMov Digital Health in Motion research unit. The experimental platform was set on the desktop of a round table with three chairs placed at equidistance from each other. Before starting the first trial, we verified the position of the chairs and table by aligning the furniture’s legs with the marks on the floor. In this way, the furniture position was identical between different groups. Participants sat at a table in the same seat throughout all trials. To ensure a

comfortable wrist position during the experiment, we fixed foam pads serving as wrist props on the table (placed at the vertices of an equilateral triangle with a side of 30 cm, see Figure 1 for illustration).



Figure 1. The experimental setup with three participants engaged in the intentional synchronization task consisting of an air version of finger-tapping (without contact surface for the fingertip). The persons in the photograph gave written consent to the publication of the photograph.

We used the Optitrack motion capture system for behavioral data acquisition. Five Optitrack Prime 13 cameras were calibrated daily prior to each experimental session. Calibration and data collection were conducted with a closed curtain to obtain the best conditions for the motion capture cameras. We recorded movement at a sampling frequency of 120 Hz. One retroreflective marker was placed on each participant's index finger of a hand of their preference. Two participants decided to use their left hand, and 58 participants opted to use their right hand. Data were inspected, preprocessed, and manually labeled in the Optitrack Motive Software (version 2.0.0).

We used the Delsys Trigno Wireless Biofeedback System for physiological data acquisition. Specifically, we used wireless Trigno Avanti EKG biosensors to record cardiac activity at a sampling frequency of 2148 Hz. Each participant positioned the biosensor according to the Delsys guide in a modified 3-lead ECG configuration. To ensure a high-quality signal, prior to affixing the biosensors, three sensor sites were cleaned to remove the dry dermis and skin oils. Then, the participants placed a V- electrode on the left side below the pectoral muscles on the lower edge of the rib cage and, in the same way, a V+ on the right side. They made sure that the electrodes were horizontally aligned. Finally, the sensor body was placed on the left side below the V- electrode. Raw ECG time series data were extracted with the Delsys EMGworks Software.

Moreover, to allow for the synchronous recording of physiological (Delsys Trigno) and behavioral (Optitrack) modalities, we used the Optitrack eSync 2 device connected to the Delsys Trigno Research+ setup. In this way, starting a recording of Motive triggered an instantaneous recording of the three Delsys EKG devices.

The emotion induction was carried out using personal mobile phones. Prior to the experiment, participants were asked to bring their mobile devices charged. Emotions were induced using the Mentimeter website[2]. The website is designated for building interactive presentations with polls and questions. Personalized presentations were carefully prepared in advance for each participant. Before starting the experiment, we opened a browser window with three tabs with personalized presentations. Considering that the slides were changed manually, a simple Python code was created to facilitate the emotion induction procedure and perform it simultaneously for three participants. In fact, after a click of the letter R, the code produced a series of commands using keyboard shortcuts. Namely, Ctrl + 1 (open the first tab), right arrow (go to the next slide), Ctrl + 2, right arrow, Ctrl + 3, right arrow.

Emotion Elicitation

[2] mentimeter.com

The emotion induction in the present experiment was performance feedback based on a comparison with the performance of two other group members. Participants were informed that there would be a subjective and an objective evaluation of their performance. The cumulative score of subjective and objective measurements would determine their place. Specifically, subjective evaluation consisted in ranking the triad members (including themselves) in relation to their task performance; objective evaluation entailed quantifying the performance with motion capture cameras. In reality, there were neither subjective nor objective results, and all the participants received manipulated and prepared in advance emotion induction stimuli. The cover story included subjective evaluation to ensure that participants were involved in the emotion-eliciting situation and objective evaluation to get participants to trust the performance feedback.

Notably, after each trial, all three participants received the same performance feedback, meaning that all participants were induced with all negative, neutral, or positive emotions. We asked the participants to check their phones so other group members could not see their results.

Positive emotion induction was "[NAME] you are the BEST" (Figure 2A), and, correspondingly, negative emotion induction was "[NAME] you were chosen the WORST" (Figure 2C). The performance feedback had three key characteristics. First, to render the manipulations personal, we personalized Mentimeter presentations so that emotion induction slides started with the participant's name. Second, to increase the impact of manipulations, we carefully selected images from the Open Affective Standardized Image Set (OASIS) (Kurdi et al., 2017) of the same arousal level but of positive valence. Fireworks were chosen as a positive stimulus (valence was 6.27 and arousal was 4.98), and a house on fire as a negative stimulus (valence was 1.73 and arousal was 5.28). Third, to highlight the performance feedback, the words best and worst are in capitals.

However, it is tricky to induce a neutral state, i.e., the control condition, with ranking performance feedback. Providing feedback about being in second place can be perceived as a negative emotional stimulus. To induce a neutral state, participants received ambiguous feedback "You are tied (best or worst) or in 2nd place" (Figure 2B).

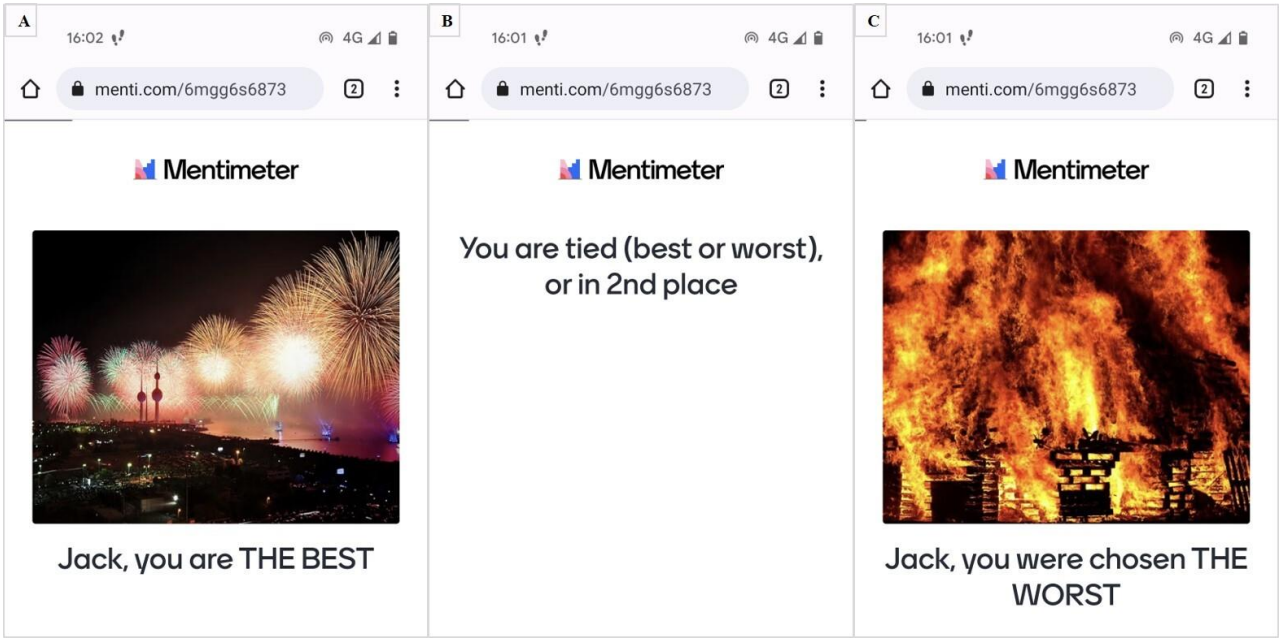


Figure 2. Emotion induction with positive feedback and positively valenced image from the OASIS database (Figure 2A), neutral state (Figure 2B), and negative emotion induction with negative valence image from the OASIS database (Figure 2C).

Experimental Task and Procedure

Upon arrival at the laboratory, participants gave their written informed consent. All participants were naïve to the study's goal and were carefully informed that the experiment investigated how personality traits shape movement and interpersonal interactions. The specific purpose of investigating emotions was not revealed in order to avoid any explicit focus on the emotional reaction. Afterward, participants were equipped with the Delsys Trigno ECG sensor, and the experimenter visually examined the QRS complex using the Delsys EMGworks software to verify the accurate positioning of the Delsys electrodes. Then, a retroreflective motion capture marker was placed on each participant's index finger.

To get participants to trust the performance feedback (i.e., emotion induction), they and the experimenter ran a test of Mentimeter ranking on the mobile device and visualized the result on a screen. By doing so, participants were reassured that their ranking was, in fact, producing results.

Afterward, participants received a practice run of the process of answering questions. Specifically, after receiving the feedback on performance, participants were asked to answer three questions on their phones. Namely, the pleasure (Figure 3A) and arousal (Figure 3B) dimensions from the Self-Assessment Manikin scale (Bradley & Lang, 1994), as well as the motivational consequences (Figure 3C) of emotion elicitation. Performance feedback and questions were displayed in French.

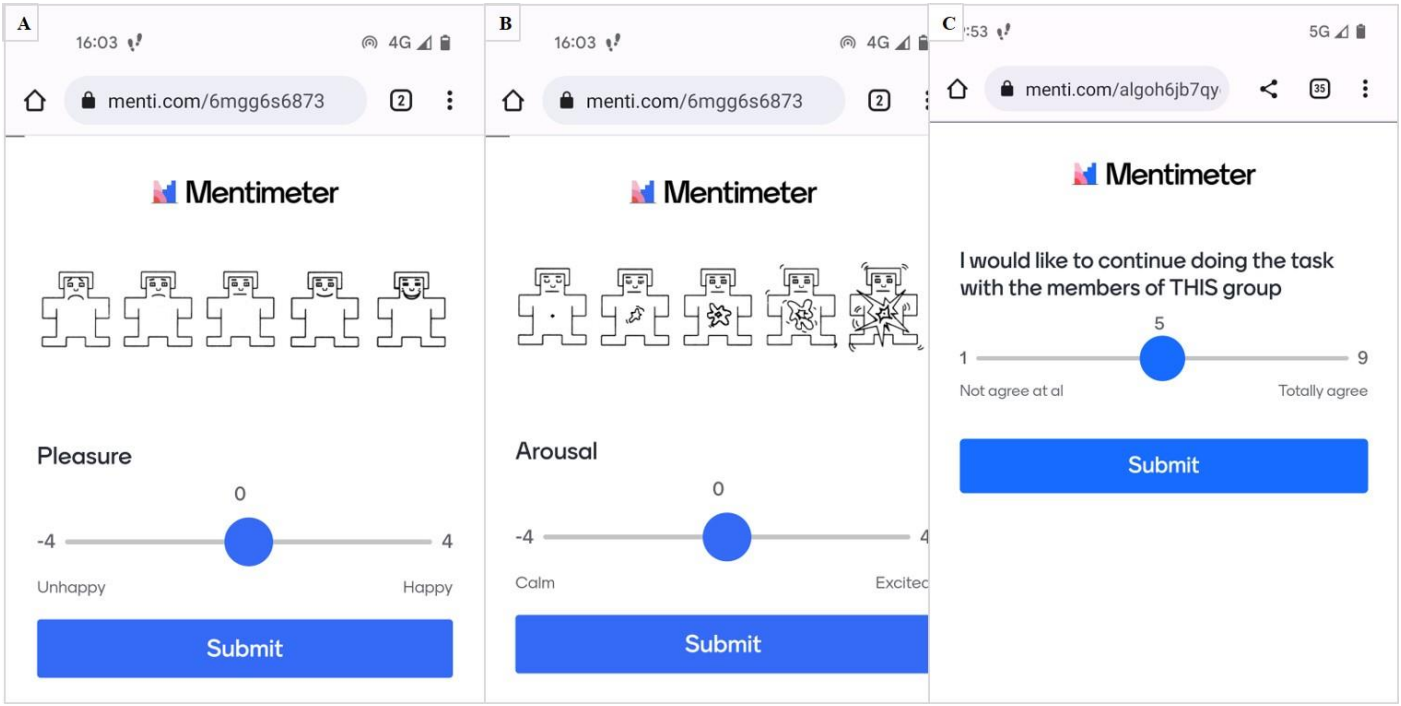


Figure 3. Evaluation of emotional [(A) pleasure; (B) arousal] and motivational (C) consequences after each performed trial.

Experimental task. Participants were asked to rest their wrists comfortably on the foam pad with their index fingers extended toward the middle of the table. The instruction was to synchronize vertical oscillations of the index finger with other group members. We choose not to tap on the table for two reasons. First, the afferent feedback from the hand to the muscles could influence motor command and rhythm production. Second, tapping on the table surface generates tactile-kinesthetic stimulation and creates noise, which improves the time-keeping precision by providing more sensory information (Drewing et al., 2002) and therefore biases the results of our task. To eliminate these potential biases, we chose a task of finger

oscillations in the air. Finally, we asked participants not to communicate during the trials to avoid verbal or any other help to synchronize.

In this experiment, we investigated the effect of emotion on interpersonal synchronization. Thus, the first trial was excluded from the analysis because it was not preceded by emotion induction. In total, the participants completed 15 trials (five trials for each of the three experimental conditions), each trial lasting 20 seconds. There was a break of about one minute between trials to rank the performances, get personal performance feedback (i.e., the same for all participants), and answer the three questions. The total duration of the experiment for a triad was about 45 minutes. Trials were randomized and counterbalanced to account for possible emotional aftereffects. Specifically, we created two random orders of trials. Accordingly, we prepared two Mentimeter presentation templates of 75 slides each. Half of the triads performed the trials accordingly to the first order, and half performed the trials accordingly to the second order (Table 3 in the supplemental materials). At the end of the experiment, the researcher debriefed the participants on the deception procedure and explained the necessity of such an experimental design.

Instruments

Self-Assessment Manikin (SAM)

The SAM scale (Bradley & Young, 1994) is a graphical and non-verbal measurement procedure that portrays human-like figures with different faces and sizes. Participants assess their subjective level of pleasure by selecting the matching facial expression of the figure and their level of arousal by choosing the corresponding size of the figure. Items are rated on a nine-point Likert-type scale ranging from -4 (unhappy) to 4 (happy) for the pleasure scale and from -4 (calm) to 4 (excited) for the arousal scale. We calculated the mean of each dimension. Internal consistencies in this sample ranged from 0.94 (*arousal*) to 0.96 (*pleasure*).

Motivational consequence

To account for the dynamics of the approach and avoidance motivation (Elliot, 1999), we included a question "I would like to continue doing the task with the members of THIS group." Given the low personal relevance of the task, we explicitly asked participants to focus on the part of the item that concerned their desire to participate in future activities with members of their triad. Item is rated on a nine-point Likert-type scale ranging from 1 (not agree at all) to 9 (totally agree). Internal consistency for the current sample was 0.82.

Data Processing and Statistics

Behavioral and physiological data preprocessing

For the behavioral data, we performed a five-step process of identifying phase synchronization (see Smykovskyi et al., 2022). First, we extracted the raw velocities. Second, we locally detrended the velocity time series signals to bring the inflection points to 0. Third, we adjusted the local maxima to 1 and local minima to -1 and generated new sine-like time series. Fourth, we performed the Hilbert transform to extract phase time series. Fifth, we performed Kuramoto order parameter analysis to detect phase synchronization.

For the physiological data, we analyzed the most salient part of the ECG time series, i.e., the QRS complex, to identify the R peaks. First, we detected R waves by using the sym4 wavelet. Then, we assigned 1 to the time stamps of the heartbeat occurrences and -1 to the midpoints between two successive heartbeats. This allowed performing the Hilbert transform for phase extraction and Kuramoto order parameter analysis for evaluating synchronization.

Synchronization Measurement

Given the movement phases $\varphi_k(t)$ of a group of interacting people $k = 1, \dots, K$ in a given time interval $t = 1, \dots, T$ a metric to measure the group level of synchronization is the Order Parameter which is calculated as follows.

Firstly, each $\varphi_k(t)$ represent a vector in 2D plane $x_k(t) = \exp(i \times \varphi_k(t)) = \cos(\varphi_k(t)) + i \times \sin(\varphi_k(t))$. This is a unit length vector. Then, the mean (this is the group mean) of these vectors is calculated for every t:

$$\overline{x}(t) = \frac{1}{K}\sum_{k=1}^{K} x_k(t) = \frac{1}{K}\sum_{k=1}^{K} \exp(i \times \varphi_k(t))$$

Finally, the order parameter is:

$$opmt(t) = |\overline{x}(t)| = \left|\frac{1}{K}\sum_{k=1}^{K} x_k(t)\right| = abs(\overline{x}(t))$$

Intuitively, if all $x_k(t)$ "point" in the same direction, i.e., $\varphi_k(t)$ are similar, then $opmt(t) = |\overline{x}(t)|$ will have values near to the maximal value of 1. On the contrary, if $x_k(t)$ are more dispersed, then $opmt(t) = |\overline{x}(t)|$ will be closer to 0 (the minimal value).

Main Synchronization Metrics

The Kuramoto order parameter was used to detect interpersonal synchronization (e.g., Alderisio et al., 2017; Bardy et al., 2021; Calabrese et al., 2021). Specifically, two metrics evaluated the synchronization dynamics of movement in and out of synchrony during the trial and the time needed to reach the specified synchronization level: Time-In-Sync (TIS) and Time-To-Sync (TTS).

The first metric (i.e., TIS) was evaluated based on the interquartile range (IQR) principle and was calculated separately for each triad for all its trials. In essence, when the data points are arranged in ascending order, the lower quartile – Q1 synchronization level – spans the threshold above which 75% of data points are, the median – Q2 synchronization level – includes the highest 50% of data points, and the upper quartile – Q3 synchronization level – covers the 25% of the highest values. The interpersonal finger synchronization levels across different triads were calculated for Q1 (M_{Q1} = 0.72 years, SD_{Q1} = 0.14, range = 0.41-0.90), Q2 (M_{Q2} = 0.86 years, SD_{Q2} = 0.08, range = 0.62-0.94), and Q3 synchronization levels (M_{Q3} = 0.93 years, SD_{Q3} = 0.04, range = 0.82-0.98). By contrast, interpersonal heart synchronization is characterized by lower scores of little variations for Q1 (M_{Q1} = 0.35 years, SD_{Q1} = 0.01, range = 0.33-0.36), Q2 (M_{Q2} = 0.53 years,

SD_{Q2} = 0.02, range = 0.48-0.56), and Q3 synchronization levels (M_{Q3} = 0.77 years, SD_{Q3} = 0.02, range = 0.74-0.81). TIS values range from 0 to 20 seconds, indicating the total time above the specified synchronization level. Time spent in synchrony in seconds is an intuitive and more easily interpretable metric than the Kuramoto order parameter, which ranges from 0 to 1.

As in our previous study (Smykovskyi et al., 2022), the weak synchronization level is of primary interest in this experiment. This is the first criterion for evaluating the dynamics of moving in and out of synchrony which includes the most significant amount of data (i.e., 75% of the highest-order parameter values). Incidentally, the word weak is essential for describing the synchronization of oscillators in the field of nonlinear dynamics (e.g., Pikovsky et al., 2001). Indeed, Strogatz (2003) stipulated weak coupling as a condition for synchronization. Humans can be viewed as weakly coupled oscillators that are distinct from mediumly coupled (e.g., humans with haptic contact such as walking hand in hand) and strongly coupled oscillators (e.g., car wheels connected by the car axle). However, to avoid confusion with coupling, we renamed the term weak synchronization level to Q1 synchronization level. Moreover, we analyze the levels of synchronization Q2 and Q3 for comparison between levels as different states uncovering group interaction.

The second metric (i.e., TTS) calculated the time required to attain the specified synchronization level (i.e., Q1, Q2, or Q3) and stay above the level for a specified amount of time. Namely, in line with our previous study (Smykovskyi et al., 2022), we selected a threshold of three seconds (Table 2 in the supplemental materials). To illustrate, if a triad in a given trial reached the Q3 synchronization level, stayed above it and then dropped before the 3-second threshold, it is considered that the triad did not achieve the TTS Q3. TTS values can range from 0 seconds, which means that the group could not reach the specified level of synchronization and, crucially, stay over it for 3 seconds, to up to 20 seconds, the participants instantly reached the given level of synchronization and remained synchronized throughout the whole trial.

Transparency and Openness

An a priori power analysis was conducted using G*Power version 3.1.9.7 (Faul et al., 2007) to estimate the required minimum sample size to test the study hypothesis. The statistical test for repeated measures within factors ANOVA was chosen. Given our past research examining associations between emotions and interpersonal synchronization, we anticipated a large effect (Smykovskyi et al., 2022). The input parameters were: the effect size f = 0.40 was selected to obtain a large $\eta_p^2 = 0.14$, with a significance criterion $\alpha = .05$, power = 0.80, one group (repeated measures design), and three measurements (experimental manipulations are positive emotion VS. neutral state VS. negative emotion). The results revealed that the minimum required sample size was $N = 12$. Therefore, with an obtained sample size of $N = 20$, the current study is adequately powered.

A total of 20 triads completed 15 trials each. One trial of synchronization between three individuals produced one synchronization score for the behavioral modality and one for the physiological modality. In total, we collected 300 behavioral and physiological scores each. However, one movement trial (out of 300) was corrupted due to technical problems. No problems were found in the collection of physiological data. Statistical analyses were performed using RStudio (version 4.1.1, R Foundation for Statistical Computing, Vienna, Austria). This study's design and its analysis were not pre-registered. Deidentified data and analysis code can be accessed at https://osf.io/5qa4j/. Finally, this manuscript was conceived in accordance with Journal Article Reporting Standards (Kazak, 2018).

It is important to determine the distributions of each variable to choose the appropriate statistical method (i.e., parametric or nonparametric test). Our sample size was $N = 20$ triads. We used the Shapiro-Wilk normality test because it is suited for small sample sizes of $N < 50$ (Mishra et al., 2019). The results of the Shapiro-Wilk normality test were verified by visually examining the QQ plots and the absence of extreme outliers (using the boxplot method, the troublesome values are above Q3 + 3*IQR or below Q1 – 3*IQR). Before implementing the repeated measures ANOVA, we verified the equality of variances between groups with Mauchly's test of sphericity. If the assumption of sphericity was violated, then the conservative Greenhouse-Geisser correction was applied and reported. Separate one-way repeated measures ANOVA were run on the three metrics of synchronization (i.e., Kuramoto order parameter, TIS, TTS) with

appropriate *post hoc* comparisons (i.e., t-test comparisons with the conservative Bonferroni correction) to detect meaningful differences between experimental conditions.

In the case of finding statistically significant differences in synchronization between conditions of emotion induction, certain healthy skepticism is necessary (Schmidt et al., 2012). Indeed, spurious chance and accidental coupling can be potential biases, and therefore it is crucial to perform a pseudo-synchrony test to account for chance synchrony (Bernieri et al., 1988; Moulder et al., 2018). This procedure consists in generating new triads, or pseudogroups, by shuffling order parameter time series from all triads and all trials and conducting statistical tests. In the absence of significant differences in pseudogroups, we confirm that the obtained results are not accidental.

The repeated measures design accounts for interindividual variability by demonstrating different effects of experimental conditions in the same subjects. However, in their recent work, Weissgerber et al. (2015) shed light on some limitations of presenting and analyzing data in repeated measures design. In particular, bar plots mask idiosyncratic changes across different experimental conditions and mislead readers by suggesting that groups are independent. In addition, the authors depicted various distributions of the paired data, resulting in identical bar plots. Lastly, Weissgerber et al. (2015) demonstrated that quantifying and visualizing differences between paired measurements unveils experimental changes across subjects. We follow their suggestion to unmask our distributions of data and produce violin plots and differences between paired measurements.

Results

This study investigated the effect of systematically manipulated emotional states on interpersonal synchronization across different modalities (i.e., behavioral, psychological, physiological) in a finger-tapping task.

Emotion Induction Effect on Interpersonal Finger Synchronization

Emotion Induction Effect on Order Parameter

A non-parametric Friedman test of differences among repeated measures between negative emotion (*Mdn* = 0.79, *IQR* = 0.09), neutral state (*Mdn* = 0.82, *IQR* = 0.10), and positive emotion (*Mdn* = 0.84, *IQR* = 0.08) was conducted and rendered a χ^2 value of 18.20 which was statistically significant ($p < 0.001$) indicating that there were significant differences between at least two emotion induction conditions. A large effect size was detected ($W = 0.54$).

Pairwise Wilcoxon signed-rank test revealed statistically significant differences in order parameter values between negative emotion and neutral state ($Z = 23$, $p = 0.004$); negative emotion and positive emotion ($Z = 3$, $p < 0.001$); but not between neutral state and positive emotion ($Z = 46$, $p = 0.080$). The results indicate that order parameter values were significantly more disrupted after negative induction than after neutral and positive inductions.

Emotion Induction Effect on Time-In-Sync

A two-way repeated-measures ANCOVA was performed to examine the effects of two independent variables, emotion and synchronization levels, on Time-In-Sync, after controlling for motivational consequences. Descriptive statistics on the main synchronization metrics of different levels are presented in Table 1 of the supplemental materials. There was a statistically significant interaction between synchronization level and emotion on the Time-In-Sync ($F(4, 170) = 15.99$, $p < 0.001$, $\eta_p^2 = 0.27$). This indicates that the effect of emotion on Time-In-Sync depends on the level of synchronization and vice-versa.

The effects of emotion ($F(2, 170) = 113.97$, $p < 0.001$, $\eta_p^2 = 0.57$) and synchronization levels ($F(2, 170) = 695.20$, $p < 0.001$, $\eta_p^2 = 0.87$) were both statistically significant. However, the effect of the covariate variable, motivational consequence, was not significant ($F(1, 170) = 0.01$, $p = 0.917$, $\eta_p^2 = 0.00$). While the simple main effects of emotion were statistically significant at all levels of synchronization ($p_{Q1} < 0.001$, $p_{Q2} < 0.001$, $p_{Q3} < 0.001$), the simple main effects of motivational consequences were all negligible ($p_{Q1} =$

0.759, p_{Q2} = 0.893, p_{Q3} = 0.844). These results demonstrate that motivation does not explain the variance of the Time-In-Sync metric.

Post hoc pairwise t-test comparisons with Bonferroni correction for Q1 synchronization level revealed that negative emotion was not statistically significantly different from the neutral state (p_{bonf} = 0.202, 95% *CI* = [-1.63, 0.06]); negative emotion was significantly different from positive emotion (p_{bonf} = 0.006, 95% *CI* = [-2.68, -0.71]); but no significant difference was found between the neutral state and positive emotion (p_{bonf} = 0.163, 95% *CI* = [-1.84, 0.02]).

Post hoc pairwise t-test comparisons with Bonferroni correction for Q2 synchronization level revealed that negative emotion was statistically significantly different from the neutral state (p_{bonf} = 0.001, 95% *CI* = [-4.24, -1.45]); negative emotion was significantly different from positive emotion (p_{bonf} < 0.001, 95% *CI* = [-5.20, -2.52]); but no significant difference was found between the neutral state and positive emotion (p_{bonf} = 0.324, 95% *CI* = [-2.27, 0.24]).

Post hoc pairwise t-test comparisons with Bonferroni correction for Q3 synchronization level revealed that negative emotion was statistically significantly different from the neutral state (p_{bonf} < 0.001, 95% *CI* = [-6.67, -4.21]); negative emotion was significantly different from positive emotion (p_{bonf} < 0.001, 95% *CI* = [-7.52, -4.96]); but no significant difference was found between the neutral state and positive emotion (p_{bonf} = 0.468, 95% *CI* = [-1.93, 0.33]).

Taken together, the *post-hoc* results across different synchronization levels indicate that participants' time spent in synchrony significantly deteriorated after negative emotion induction. Moreover, Figure 4A depicts that with the transition to higher synchronization levels, the disruptive effect of negative emotion induction on Time-In-Sync becomes increasingly more salient. Conversely, while the induction of positive emotions contributed to time spent in synchrony and yielded the highest scores across all synchronization levels, the gain was not substantial compared to neutral induction.

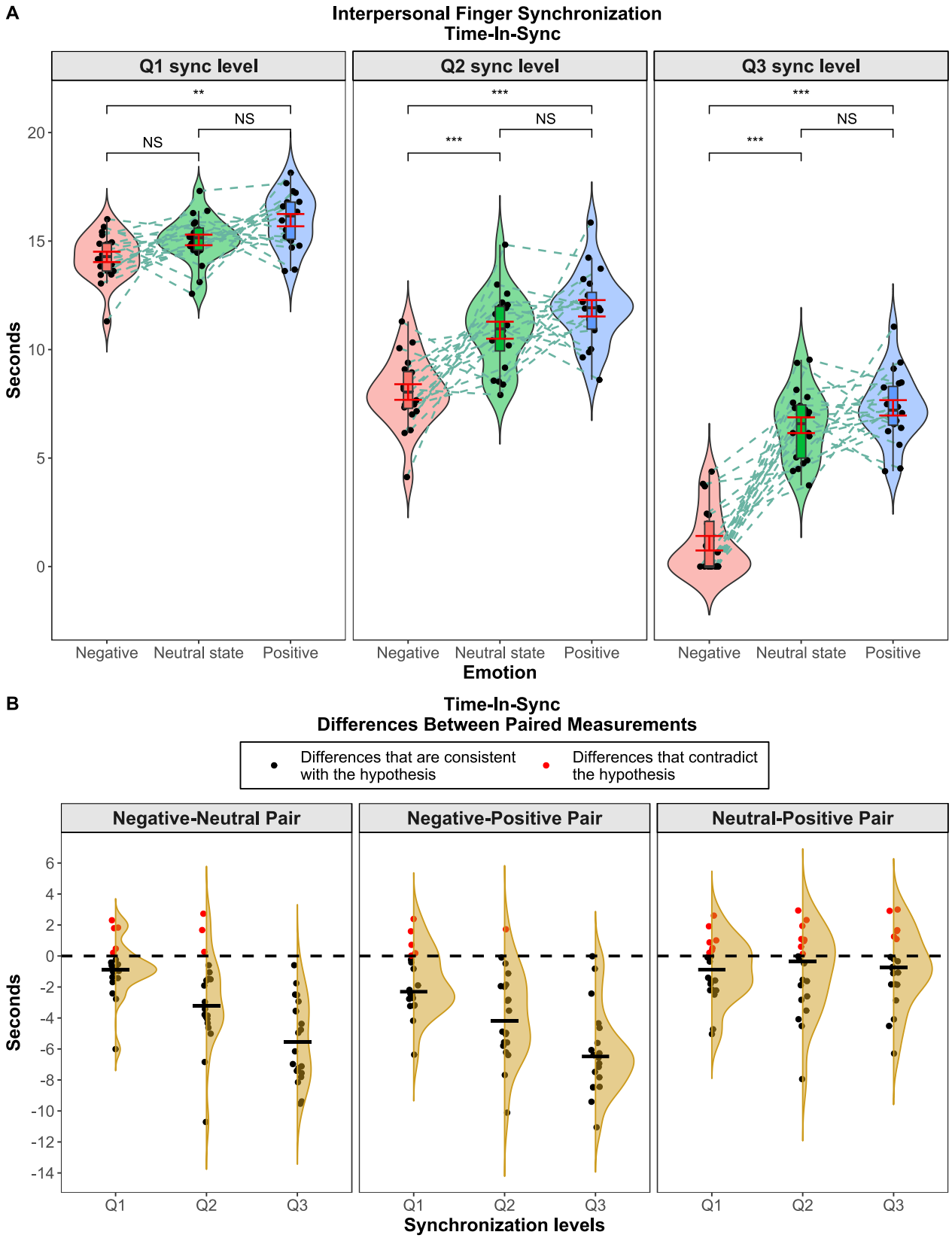


Figure 4. (A) Time-In-Sync violin plots demonstrating distributions of scattered data points for Q1, Q2, and Q3 synchronization levels. The red error bars are quantified with the standard error of the mean. Each triad's data points are connected with dashed lines. (B) Differences between paired Time-In-Sync measurements

with flat violin plots. The black dashed line indicates the hypothesis threshold, where the values lower than 0 align with the hypothesis (black data points), and the values above 0 contradict the hypothesis (red data points). The black vertical crossbars indicate medians of emotion pairs.

We performed a pseudo synchrony check to test whether the obtained results were due to chance. After shuffling trials, the repeated measures ANOVA did not detect a significant main effect of emotion ($F(2, 38) = 0.45$, $p = 0.643$, $\eta_g^2 = 0.02$). This outcome confirms that the Time-In-Sync results are not spurious.

Differences Between Paired Time-In-Sync Measurements

Given the recommendations of Weissgerber et al. (2015), we demonstrate violin plots with differences between paired measurements for time intentionally spent in synchrony (Figure 4B). The median differences between emotion induction pairs are measured in seconds and represent the Q1 level for negative-neutral (*Mdn* = -0.87), negative-positive (*Mdn* = -2.30), and neutral-positive (*Mdn* = -0.88); Q2 level for negative-neutral (*Mdn* = -3.19), negative-positive (*Mdn* = -4.20), and neutral-positive (*Mdn* = -0.37); Q3 level for negative-neutral (*Mdn* = -5.55), negative-positive (*Mdn* = -6.48), and neutral-positive (*Mdn* = -0.75) emotion. Notably, all medians have a negative sign. In addition to negative medians, the distributions are skewed towards negative values. These outcomes reveal that the results for all three pairs of emotions are consistent, albeit to varying degrees, with our hypothesis regarding the expected effects of emotion induction.

However, not every triad was prone to emotion induction by the same token. Indeed, there is a curious pattern comparing paired differences between the neutral and positive emotion induction pairs (Figure 4B). In fact, some pairs (e.g., neutral-positive Q1 and Q2 levels) have no data points around the median. This illustrates that our sample can be bimodal. In essence, the neutral and positive paired differences visualization shows two types of groups: the groups with paired differences far below the median that reacted in accordance with our hypothesis and the other group with paired differences far above the median

for whom emotion induction had an opposite effect. This represents a promising avenue for uncovering individual sensitivity to emotion induction procedure, meaning to what extent some individuals are prone to a particular emotion induction.

Emotion Induction Effect on Time-To-Sync

A two-way repeated-measures ANCOVA was planned to examine the effects of two independent variables, emotion and synchronization levels, on Time-To-Sync, after controlling for motivational consequences. However, we could not perform the analysis because i) while all the triads achieved a Q2 synchronization level after the neutral state and positive emotion inductions, eight triads did not attain the Q2 level after negative emotion induction, and ii) while almost half the triads did not attain the Q3 level after the neutral state and positive emotion induction, none attained the Q3 level after negative induction creating a fully missing variable (Figure 1 in the supplemental materials). This result further consolidates and stresses the perturbing effect of negative emotion on interpersonal finger synchronization.

Emotion Induction Effect on Pleasure, Arousal, and Motivational Consequences

A non-parametric Friedman test of differences among SAM pleasure repeated measures between negative emotion (*Mdn* = 1.73, *IQR* = 1.95), neutral state (*Mdn* = 2.00, *IQR* = 1.62), and positive emotion (*Mdn* = 2.47, *IQR* = 1.05) was conducted and rendered a χ^2 value of 7.06 which was statistically significant (p = 0.029) indicating that there were differences between at least two different emotion induction conditions. A small effect size was detected (W = 0.18).

Pairwise Wilcoxon signed-rank test of differences among SAM pleasure values revealed statistically nonsignificant differences between negative emotion and neutral state (Z = 46, p = 0.087); significant differences between negative emotion and positive emotion (Z = 35, p = 0.022); and nonsignificant differences between the neutral state and positive emotion (Z = 38.5, p = 0.073). The results indicate that

SAM pleasure values were significantly improved after positive emotion induction and diminished after negative emotion induction.

A non-parametric Friedman test of differences among SAM arousal repeated measures between negative emotion (*Mdn* = 0.90, *IQR* = 1.58), neutral state (*Mdn* = 1.00, *IQR* = 1.63), and positive emotion (*Mdn* = 1.03, *IQR* = 1.68) was conducted and rendered a χ^2 value of 2.18 which was statistically nonsignificant ($p < 0.336$) of a small effect size was detected ($W = 0.06$). This outcome suggests that the emotion induction manipulations did not produce self-conscious and substantial changes in arousal.

A non-parametric Friedman test of differences among motivational consequences repeated measures between negative emotion (*Mdn* = 6.78, *IQR* = 0.92), neutral state (*Mdn* = 6.97, *IQR* = 1.17), and positive emotion (*Mdn* = 7.03, *IQR* = 0.97) was conducted and rendered a χ^2 value of 9.66 which was statistically significant ($p = 0.008$) indicating that there were differences between at least two different emotion induction conditions. A small effect size was detected ($W = 0.24$).

Pairwise Wilcoxon signed-rank test performed on motivational consequences revealed statistically nonsignificant differences values between negative emotion and neutral state ($Z = 69$, $p = 1.000$); significant differences between negative emotion and positive emotion ($Z = 19$, $p = 0.021$) and between the neutral state and positive emotion ($Z = 20$, $p = 0.014$). These results indicate that motivational consequence values were significantly enhanced after positive emotion induction.

Emotion Induction Effect on Interpersonal Heart Synchronization

Emotion Induction Effect on Order Parameter

A non-parametric Friedman test of differences among repeated measures between negative emotion (*Mdn* = 0.55, *IQR* = 0.04), neutral state (*Mdn* = 0.55, *IQR* = 0.03), and positive emotion (*Mdn* = 0.55, *IQR* = 0.02) was conducted and rendered a χ^2 value of 18.20 which was not statistically significant ($p = 0.522$) and of a

small effect size ($W = 0.03$). These results reveal no significant differences between different emotion induction conditions.

Finally, the Kuramoto order parameter values for interpersonal synchrony for physiological modality were considerably lower than one found for behavioral modality (Figure 5). A Wilcoxon rank-sum test conducted on trial medians indicated that the finger order parameter values, $Mdn = 0.88$, were statistically significantly higher than the heart order parameter values, $Mdn = 0.53$, $W = 86988$, $p < 0.001$, $\hat{r}_{\text{rank biserial}} = 0.94$, CI $_{95\%}$ [0.91; 0.96], $n_{\text{obs}} = 599$. The implications of this finding are further discussed.

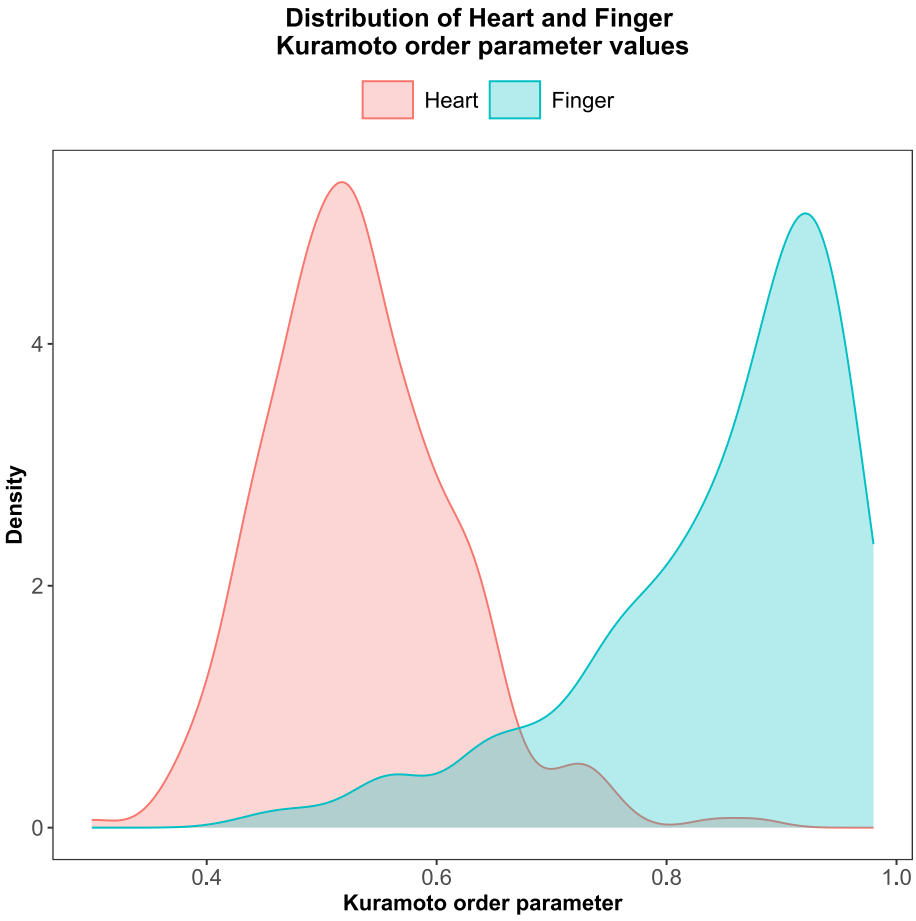


Figure 5. Density plots demonstrating distributions of trial median values of Heart and Finger order parameters.

Emotion Induction Effect on Time-In-Sync

Mauchly's test of sphericity indicates that the assumption of sphericity has been violated, $\chi^2(2) = 0.64$, p = .019. Therefore, the repeated measures ANOVA with Greenhouse-Geiser correction conducted between negative emotion ($M = 14.92$, $SD = 0.46$), neutral state ($M = 14.76$, $SD = 0.45$), and Positive emotion ($M = 14.90$, $SD = 0.68$) did not reveal a significant main effect of emotion induction on Time-To-Sync ($F(1.47, 27.99) = 0.34$, $p = 0.651$, $\eta_g^2 = 0.02$).

Emotion Induction Effect on Time-To-Sync

Repeated measures ANOVA conducted between negative emotion ($M = 5.64$, $SD = 2.71$), neutral state ($M = 5.85$, $SD = 3.77$), and positive emotion ($M = 5.52$, $SD = 2.99$) did not reveal a significant main effect of emotion induction on Time-To-Sync ($F(2, 24) = 0.56$, $p = 0.577$, $\eta_g^2 = 0.03$).

Discussion

Behavioral Modality

The current study examined the effect of emotion induction based on success-failure manipulation on intentional interpersonal synchronization. Results indicated that negative emotion induction substantially perturbed intentional finger synchronization. The results of three measures contributed to this conclusion.

First, the negative emotion induction considerably reduced the raw order parameter values relative to the neutral state and positive emotion. Nevertheless, there were no significant differences between the neutral state and positive emotion.

Second, negative emotion induction shortened the time spent in Q1 synchronization–Time-In-Sync (TIS) measure– relative to positive emotion by 2.3 seconds. Although TIS *post hoc* pairwise comparisons confirmed the significant differences only between negative and positive emotion inductions, differences between paired measurements demonstrated alignment with our hypothesis for the other two emotion induction pairs. Indeed, the neutral state improved the TIS values after negative emotion and positive

emotion improved the TIS values after neutral state induction by almost 1 second for each pair. Moreover, TIS Q2 and Q3 synchronization levels (Figure 4A) depicted that, like in order parameter values, the negative emotion induction significantly shortened time spent in synchrony relative to both neutral state and positive emotion. In line with the Q1 order parameter results, neither the Q2 nor Q3 synchronization levels exhibited meaningful differences between the neutral state and positive emotion.

Third, the time necessary to attain synchronization–Time-To-Sync (TTS) measure–was not significant for either of the synchronization levels. Nevertheless, the higher the synchronization level, the more prominent was the difficulty in attaining synchronization after the induction of negative emotions (Figure 1 in the supplemental materials). As a matter of fact, while all the triads reached the Q2 synchronization level after the induction of a neutral state and positive emotion, almost half of the triads did not reach the Q2 level after negative emotion induction (Table 1 in the supplemental materials). Remarkably, no triad achieved a Q3 synchronization level after the negative emotion induction.

> *Hypothesis 1*: The induction of negative emotions will result in lower synchronization scores than the neutral state (i.e., lower Time-In-Sync and higher Time-To-Sync metrics).

We examined whether negative emotion induction leads to synchronization impairment and generates the lowest synchronization scores of the three experimental conditions. Supporting H1, we demonstrate a consistent results pattern between order parameter values and TIS concerning dropped synchronization scores after negative emotion induction. We noted an absence of significant effect in the TIS pseudo-synchrony check, as well as difficulties in attaining synchronization for TTS Q2 and Q3 levels after the induction of negative emotions, which we conclude as confirmation of our first research hypothesis.

One possible explanation for the finding is that the processing of negative emotions increases cognitive load. Motivation and individual cognitive resources moderate interpersonal emotional effects, in which mental effort is positively associated with the predictive power of affective reactions (van Kleef, 2009). Moreover, increased cognitive demand for negative emotions, such as anxiety, hindered fluid cognition and the ability to process the demands of unusual tasks and offered innovative solutions (Moran, 2016). However, in the

present experiment, the task of cyclic sensorimotor interaction did not require a creative mental effort but exploited concentration to a greater extent. Moreover, if negative emotions are the cause, then mental efforts associated with processing positive emotions should not increase. Yet, positive emotions have also been found to intensify mental efforts (Um et al., 2012). For these reasons, the cognitive load explanation is not entirely convincing in this experiment, and future research should explore in depth the triangular relationship between participants' cognitive resources, synchronization task requirements, and the mental effort associated with processing different emotions.

> *Hypothesis 2*: The induction of positive emotions will result in higher synchronization scores than the neutral state (i.e., higher Time-In-Sync and lower Time-To-Sync metrics).

In line with our previous study (Smykovskyi et al., 2022), we verified whether positive emotion strengthens synchronization and generates the highest synchronization scores. We did not detect a statistically significant improvement in positive emotion induction with respect to the neutral state. One explanation is that the intentional nature of the task allows for different outcomes. In contrast with our previous study, an improvisational task in which participants spontaneously synchronized, the present experiment was more controlled, and the synchronization of movement oscillations was performed intentionally. Possibly, while spontaneous synchronization is more prone to changes in positive emotion, intentional synchronization is more sensitive to negative emotion. However, we lean towards another explanation, which is a difference in the perceived relevance of emotion induction. In fact, in our preceding study, the participants were engaged in an activity they considered personally relevant (i.e., dancing for dancers). For this reason, the emotion induction based on success-failure feedback was conceivably high. By contrast, the activity of the present study (i.e., finger-tapping) was not considered personally relevant. Improving the relevance of emotion induction will potentially enhance the magnitude of differences. Indeed, despite the absence of a significant effect, positive emotion induction yielded the highest synchronization scores across all major indicators (i.e., order parameter, TIS Q1, TIS Q2, TIS Q3). This exploration suggests that the higher the perceived relevance of emotion induction, the greater the effect on movement synchronization, at least up to a certain threshold.

Psychological Modality

Some readers may challenge our view by insisting that the observed effects on behavioral modality can be due to an improved motivation to perform the task and not due to emotion induction. Social psychologists clearly distinguish motivation and emotion as separate theoretical constructions. However, it is unrealistic to separate the two entities in practice. In fact, motivation and emotion use the same neural circuitry (Lang & Bradley, 2015). Moreover, the insistence of some theories (e.g., Frijda et al.'s (1989) action tendencies) on motivation to engage in specific activity (i.e., anger to fight and fear to flight) further emphasizes the complexity of distinguishing these two theoretical constructions. Emotions are intrinsically motivational. According to Elliot's (1999) approach-avoidance motivation distinction, the former entails inclination towards a desired stimulus, and the latter constitutes withdrawal from an undesired stimulus. Just as anger could incite aggressive behavior towards a source of danger, fear can incite moving away from the danger. More specifically to our study, while some might react to the personalized social feedback "[NAME], you were chosen the worst" with anger and an amplified will to perform the task (i.e., approach), others might react with indifference, detachment and even sabotage (i.e., avoidance). That is why we introduced the motivational consequence question that detects the dynamics of approach and avoidance mindset. Moreover, motivation was used as a covariate of the Time-In-Sync metric and yielded non-significant results. We found that, relative to the neutral state, the negative emotion induction did not deflect the will to engage in future activities. At the same time, participants reported higher approach scores after positive emotion induction. This is important because fostering the approach motivation allows for generating cohesive groups.

With respect to psychological dynamics captured with the SAM scale as a response to systematic emotion induction, we observed alterations in pleasure but not arousal scores. These results are consistent with our previous study (Smykovskyi et al., 2022) and are in line with previous literature (Joseph et al., 2020; Nummenmaa & Niemi, 2004). Evidently, the valence dimension can be robustly targeted with personalized success-failure feedback manipulations. Taken together with behavioral results, we conclude that the emotion induction of the present study was successful. Interestingly, unlike our previous study, the present

results confirm a well-established negativity bias (Joseph et al., 2020; Rozin & Royzman, 2001). In the task of low personal relevance, negative emotion induction is more efficient and generates changes of higher magnitude than positive induction.

Physiological Modality

In relation to the effect of emotion inductions on physiological modality, synchronization scores of interpersonal heart activities were not meaningfully different. This result is consistent with our previous study (Smykovskyi et al., 2022). In our previous experiment, participants were standing and moving. In such a context, the movement typically affects to a greater extent the Autonomic Nervous System (ANS) rather than social comparison feedback. To control for the movement bias, the participants were seated in the present experiment. Indeed, gross movements were excluded, and participants only moved their index fingers. The present results corroborate that movement was not a bias in our previous study. The explanation is twofold.

On the one hand, we could interpret that the effect of emotion induction was not strong enough to produce discernable changes in heart rate activity. In fact, Wallot et al. (2016) already evidenced a lack of heart rate synchrony during a joint action activity. Notwithstanding the evidence, the authors emphasized the lack of strong emotional reaction to the task as a possible explanation for the absence of physiological sync. Indeed, when the emotional response is strong, such as the connection between relatives in a fire-walking ritual (Konvalinka et al., 2011), the between-person heart rate activity tends to synchronize. One of the future avenues of research on interpersonal synchronization is to determine the threshold of emotional intensity, after which one can detect cardiac attunement between people.

On the other hand, it is possible that the physiological response was indeed triggered. However, while order parameter analysis was suitable for identifying behavioral synchronization, it failed to detect physiological attunement. The evidence of between-person physiological synchrony is robust and was recently stressed in three literature reviews (Kazi et al., 2021; Mayo et al., 2021; Palumbo et al., 2017). Moreover, empirical

evidence of heart rate synchronization during joint action is ample (e.g., Baranowski-Pinto et al., 2022; Lange et al., 2022; Tomashin et al., 2022). In our experiments, we performed the same Kuramoto order parameter analysis to homogenize the analysis across behavioral and physiological modalities. While movement variation can be considerable, heart rate changes are subtler and are bounded within physiological limits. Specifically, voluntary changes in movement can easily adjust interpersonal finger synchronization, but heart rate cannot change as dynamically because the changes are gradual and relatively slower. For instance, an adult American's average resting heart rate varies between 60 and 90 beats per minute (Ostchega et al., 2011), and cardiac activity is characterized by small intrinsic variability (Constant et al., 1999). We demonstrated that the Kuramoto order parameter values are visibly diminished for physiological modality (Figure 5). Arguably, in addition to the phase analysis, the two most common techniques to detect synchronization are correlational and recurrence quantification analyses. While the former averages out the meaningful dynamics, which was shown to be the essence of synchronization (Mayo & Gordon, 2020), the latter could not be performed on our data due to insufficient data points–i.e., heartbeats–during 20 seconds trials. Consequently, we encourage future research to establish synchronization-detection algorithms depending on the nature of the data.

Implications

From a theoretical perspective, this manuscript produces empirical justification for including emotion in the human synchronization models to better understand interpersonal behavior and coordination. Our results empirically support Sapolsky's (2017) claim that negative emotions constitute the mechanism for social detachment. In the long run, interpersonal emotion research will also contribute to the field of social opinion engineering (Bernays, 1928) through collective effervescence (Durkheim, 1995).

From an applied perspective, the results of this research can be used in the facilitation of Autism Spectrum Disorder adaptations (Manders et al., 2021) and in techniques improving interpersonal bonding (Fuchs & Koch, 2014) by encouraging instances of congruent rhythmical behavior to generate shared positive

emotions. Also, we have demonstrated the necessity of choosing an interpersonal synchronization detection analysis that is data dependent (i.e., small intrinsic variability of cardiac activity and large variability of movements). Finally, these findings will contribute to the current technology trend that emphasizes the development of emotion-aware devices that promote student learning (Feidakus, 2016; Muñoz et al., 2020), facilitate decision-making on the battlefield environment (Lin et al., 2019), assists in healthy aging (Mieleszczenko-Kowszewicz et al., 2022) and more generally increases wellbeing and quality of life (Zhou et al., 2009).

Constraints on Generality

Our findings provide evidence of the emotional effect on rhythmic interaction in participants who were induced with success-failure manipulations. Given that this effect has been observed for a range of participants in a series of experiments on spontaneous and intentional synchronization in our laboratory, we expect our result to generalize to other contexts in which persons are engaged in rhythmical tasks as long as participants genuinely experience emotional states (i.e., the emotion induction method does not sacrifice ecological validity). One limitation of the present work is that the task is constrained. This was identified as a common weak spot of interpersonal coordination research (Bente & Novotny, 2020). While it is true that the present task is structured to movements only in one dimension, it allows for a controlled experimental design and a reliable answer to our research question of the effect of emotion induction on intentional group synchronization. Future studies shall focus on moving toward more naturalistic tasks. Finally, we expect that individual and cross-cultural differences may moderate the observed experimental findings. In this study, we accounted for personality traits (i.e., neuroticism and extraversion), emotional contagion, and mood, but given the lack of significant explanatory contribution to the analysis, these variables were left out of the scope of this article.

Conclusions

In this manuscript, we demonstrated that emotion induction altered participants' movement oscillations in an intentional finger-tapping task. Negative emotions influenced detrimentally interpersonal synchronization performance. This is a piece of empirical evidence that negative emotion may function as an instrument of restraint and protection, manifested by a tendency of withdrawal from undesired social interaction and revoking affiliation. Therefore, to unravel why and how humans synchronize, emotion is a key variable for seizing the dynamics of interpersonal coupling alongside perceptual interaction.

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Summary of Chapter 9

The third publication shed light on the effects of emotion induction on group sensorimotor synchronization in a structured experimental context. The results of the time intentionally spent in synchronization (i.e., Time-In-Sync metric) revealed that negative emotion induction was significantly lower than positive induction across all three, Q1, Q2, and Q3, synchronization levels. Similarly, there was a significant decrease in Time-In-Sync scores after negative emotions compared to the neutral state at synchronization levels Q2 and Q3. Importantly, the pseudosynchrony test ascertained that the result was not due to chance. Moreover, we controlled for the motivational consequence of the emotion induction which did not have a predictive power in the Time-In-Sync metric. This result suggests that the engagement in the experimental task was not changed after receiving evaluative feedback of being the worst or being the best in the preceding trial.

The emotion induction based on success-failure manipulations was successful even in the task of little personal relevance. This conclusion rests upon the produced changes across behavioral and psychological modalities. Being involved in the process of emotion induction as well as getting personalized feedback compensates for the task having little personal significance (i.e., oscillating index fingers).

However, the physiological scale demonstrated around-chance level synchrony for the Time-In-Sync. This result indicates that either i) the emotion induction procedure used in this experiment did not produce discernable changes at interpersonal cardiac synchronization or ii) the Kuramoto order parameter analysis is not adapted to detect the subtle changes that interpersonal cardiac synchronization entails.

Part V

GENERAL DISCUSSION AND CONCLUSION

CHAPTER 10

Summary of this dissertation and future work

This dissertation posits within the broader field of social neurosciences and intersects with coordination dynamics and affective computing. Despite the prominent role emotions play in shaping social interactions and impacting behavior, their influence on joint action processes has not received adequate attention in previous research. There are several limitations that can account for the scarcity of research in this area. For instance, the utilization of various disparate methods in social neurosciences leads to inconsistent and sometimes contradictory findings, impeding the generalizability of the results. Second, studies focusing on emotions often compromise the ecological validity of emotion induction, thus restricting the extent to which the findings can be applied to diverse contexts. Third, the studies on emotions in an interpersonal context frequently focus on only dyadic interactions, neglecting the broader social dynamics that occur within larger groups and everyday contexts. Fourth, the social interaction analysis often focused on singular modalities, such as behavior or physiology alone, thereby disregarding the complex emergent processes that arise from the simultaneous interaction of multiple modalities at the organismal level. These limitations encompass the challenges that must be addressed to expand the existing boundaries of knowledge and investigate the integration of joint action and emotions within more ecologically valid and socially representative settings. Therefore, the objective of this dissertation was to tackle those limitations and gain a deeper understanding of the intricate interconnectedness of human joint action and emotions.

This doctoral dissertation addresses the aforementioned limitations through the presentation of four distinct contributions. First, we conducted a theoretical evaluation of existing accounts that provide substantiation for the significance of emotions in the realm of joint action research. Second, we analyzed and juxtaposed computational methods that has been used in evaluating interpersonal synchronization. Third, we introduced an innovative method for inducing emotions that simultaneously ensures both high ecological validity and high experimental control. Fourth, through a series of two distinct experimental investigations, we examined the impact of emotions on interpersonal syn-

chronization within both unstructured and structured experimental contexts.

In this section, we provide a comprehensive overview of the research carried out in this thesis through three interrelated research themes i) theoretical, ii) methodological, and iii) experimental. We summarize and discuss the significant contributions we have made within each of these themes. Moreover, we acknowledge the limitations and constraints of our own work, reflecting on areas where improvements and further investigations can be pursued to extend and enhance the scope of this dissertation.

10.1 Summary of this dissertation

In this section, we provide a concise summary of the work that has led to the development of four distinct contributions, each of which directly addresses the original research question that was posed during my PhD program, serving as a foundation for further exploration and analysis. This summary serves as a valuable reference point for readers to grasp the scope and contributions of the study, setting the stage for the subsequent discussions and conclusions.

10.1.1 Theoretical theme: Emotions in human joint action

To put it briefly, the primary focus of the first theme, and the first publication, was to examine the theoretical benefits of combining two distinct areas of research, specifically emotion and joint action, within the field of social neuroscience. Initially, we conducted individual analyses and discussions on each of the research strands. Subsequently, we expanded the scope of our research to domains that are currently investigating the integration of these two research strands. These research domains include investigations concerning patients experiencing social interaction disorders, as well as interactions involving human-computer and human-robot interactions. We put forth the argument that interpersonal synchronization models have predominantly prioritized the examination of behavioral aspects, neglecting the potential benefits that can be derived from incorporating emotional components. Through a review of the available information, we have identified outstanding research questions that have the potential to shape future trajectory of studies in the field at large. Moreover, these insights have directly influenced the formulation of research questions within this dissertation.

> **Research question № 1**: How does integrating emotion research into the study of human joint action contribute to a deeper understanding of interpersonal synchronization processes?

To gain a deeper comprehension of the potential contributions of emotions to joint action research, it is necessary to explore the underlying reasons for their oversight. Upon

thorough examination of this matter, we are compelled to propose two key factors that contribute to the lack of consideration for emotional effects. First, the tendency to concentrate on non-emotional situations to understand social interactions fails to account for the frequent occurrences in which emotions arise and significantly impact behavior. Second, there is a challenge in effectively inducing genuine emotions, and neurobiological evidence offers valuable insights to address this challenge.

First, it is important to recognize that not every instance of joint action is inherently imbued with emotions. Indeed, in certain contexts, the emphasis is on coordination and achieving common objectives without a strong emotional component. In addition, it has been demonstrated that in the context of interpersonal synchronization, beneficial outcomes such as fostering cohesion can be achieved even without the presence of positive emotions, such as joy (Wiltermuth and Heath, 2009). However, while not every interaction is inherently emotional, we often find ourselves sharing and expressing our emotions in the presence of others (van Kleef, 2016). In such cases, a dynamical, oftentimes reciprocal process unfolds in which an exchange of emotions takes place, exerting a transformative and influential force on our perceptions, experiences, and social interactions (Butler, 2011). Considering this perspective, a fundamental inquiry emerges: Under which circumstances do emotions come into play? As discussed in Chapter 3 of this dissertation, emotions serve as relevance detectors that activate various internal subsystems, and guide an agent's behavior in its environment (Sander et al., 2003). Consequently, emotions emerge when there is a discrepancy between what an agent subjectively deems relevant and the perceived circumstances in their environment. Such a discrepancy occurs regularly, leading to the manifestation of various emotions. Neglecting the morphogenic impact of emotions in joint action would mean disregarding the significance they hold in interaction. This oversight disrupts the intricate linkage between perception and action, ultimately distancing individuals from their environment. This line of reasoning substantiates the need to incorporate emotions into the study of joint action, illuminating how human behavior embodies the dynamics of perception-action.

In the long run, simulations of human social behavior using coupled oscillators models will require incorporating emotion (i.e., relevance detector) as a parameter that influences between-person coupling. By following the functions of emotion, such as attention-driven, informational, and motivational, as synthesized by Reisenzein (2015), the inclusion of emotions in the simulations becomes instrumental in explaining the underlying mechanisms that drive attention. This inclusion also lays a foundation for establishing interpersonal coupling (e.g., Dikker et al., 2017), prompting agents to computationally attend to stimuli, gather relevant information, and initiate adaptive actions. Understanding how interpersonal coupling emerges and unfolds is important because,

as Strogatz (2003) warned, the transition from studying self-sustained coupled oscillators in physics to studying humans necessitates a departure from the familiar all-to-all coupling framework. In the context of human systems, individuals no longer experience simultaneous influence from and influence upon every other individual within the system, highlighting the need for a distinct understanding of the complexities inherent in human interactions. To expand the application of coupled oscillator logic to the study of human dynamics, we propose the integration of attention and emotion (i.e., subjective relevance) as pivotal parameters. The interaction between attention and emotion in establishing coupling seems to involve, at least, a two-step progression. Initially, attention narrows down the selection from a pool of individuals, or "oscillators", within an individual's environment. Subsequently, emotion overlays a nuanced layer that determines whom to approach and from whom to withdraw, further shaping the dynamics of interpersonal connections.

Second, in addition to restricting focus to non-emotional contexts, the possible second explanation for the oversight of emotional effects on joint action is that the procedures designed to induce emotions often do not consistently succeed in evoking genuine emotional responses. Instead, these procedures frequently involve the activation of other affective constructs, such as feelings, moods, or preferences (e.g., Scherer, 2005). At this stage, it proves advantageous to explore how emotion induction is approached in other research fields, enabling the integration and enrichment of techniques employed outside social neuroscience research. The disciplines of neurobiology and social opinion engineering have emerged as particularly robust and impactful in eliciting and shaping emotional responses. Their notable achievements primarily stem from focusing on sources that hold personal relevance. For instance, in a classic example involving mice, neuroscientists (Maren, 2001) employ classical Pavlovian fear conditioning by associating a neutral stimulus, such as light, with an emotionally arousing stimulus like an electric shock. Conversely, propaganda (Bernays, 1928) targets public opinion by evoking emotions through messages that are contextualized, personally relevant, and aligned with cultural norms and collective beliefs. By strategically utilizing emotions such as fear, anger, pride, and disgust, the propaganda techniques manipulate and mold public opinion (Sapolsky, 2022). Nevertheless, a more empirically verifiable approach lies in the domain of neurobiology, which we will explore in greater depth.

Based on the locationist approach (see Lindquist et al., 2012), it was suggested that the amygdala serves as a specialized brain module responsible for processing fear (Mineka and Ohman, 2002). Fear, being recognized as a basic emotion, has received extensive scrutiny from neuroscientists across various disciplines. Even in the present time, it continues to capture and concentrate significant attention from researchers in the field (e.g., Mobbs et al., 2019). Why do neuroscientists devote considerable attention to one

particular emotion while potentially neglecting others? The primary rationale behind this lies in the relative ease of creating survival-threatening situations and inducing immediate behavioral responses in animals, primarily withdrawal, through stimuli manipulation (LeDoux and Pine, 2016). Moreover, humans exhibit a predisposition to prioritize the processing of negatively-valenced information over positive ones (Baumeister et al., 2001). This predisposition is rooted in the fact that negative and positive information are processed through distinct neural circuits (Vaish et al., 2008). In their work, (LeDoux and Pine, 2016) highlighted that there is neither a distinct "fear module," such as the amygdala, nor a dedicated neural circuit solely responsible for fear-related processes. Contrary to the notion of a separate fear module, research on primate animals, as demonstrated by Sander et al. (2003), suggests that the amygdala has evolved as a center for detecting environmental relevance, which includes the processing of fear. Neurobiological evidence highlights the intricate interplay between what we typically label as emotions and the broader perception of stimuli' relevance in the environment. This underscores the notion that for emotions to be effectively elicited, it is necessary to appropriately manipulate the perceived relevance of stimuli for the participants involved.

10.1.2 Methodological theme: Operationalization of interpersonal synchronization

In a nutshell, the main intention of the second theme in this dissertation was to examine the existing computational strategies utilized for evaluating interpersonal synchronization. Specifically, our review encompassed proof-of-concept tutorials as well as comparative articles that shed light on the performance of different analytical tools. Additionally, we analyzed how synchronization is operationalized across diverse academic disciplines, identifying both similarities and inconsistencies. We also reiterated the definition of interpersonal synchronization from nonlinear sciences and elucidated the dimensions through which it can be examined. Finally, we presented comparisons among different methods on data with distinct characteristic and advocated for the utilization of phase-based analysis, which reflects rhythmic adaptations between agents, as a preferable approach over the commonly used methods of estimating the similarity of signals.

> **Research question № 2**: Which methodological approach yields the highest accuracy and reliability in measuring interpersonal synchronization during social interactions?

10.1.3 Experimental theme: Effects of emotions on interpersonal synchronization

The central mission of the experimental theme was to empirically test the obtained insights gained in theoretical and methodological themes and reveal the effect of emotions on social interaction. Specifically, we extended our investigation beyond the conventional dyadic interaction and explored group interaction involving three individuals. Moreover, we focused on developing a naturalistic method for inducing emotions and exploring their effects on interpersonal synchronization within unstructured and structured experimental contexts. Finally, rather than relying on a commonly employed unimodal approach that fails to capture the holistic nature of human experience, we used a multimodal approach that simultaneously analyzed behavior, physiology, and psychology. Accordingly, the experimental theme gave rise to two research questions. One with regards to the method of emotion induction and the other with regards to the type of effects observed.

This research theme aligns with the recent call for interdisciplinary consensus on the definition of synchrony, as highlighted in the Nature publication by (Ravignani, 2017). The study of synchronization spans diverse domains, ranging from physics to biology. Therefore, it is not surprising to have a myriad of different ways which researchers conceptualize the phenomenon. Pikovsky et al. (2001) argued that the use of the term synchronization reflects "the background, individual viewpoints and taste of a researcher". This emphasizes the critical importance of precisely defining the terminology and reaching a consensus on how to operationalize the phenomenon of interpersonal synchronization.

Upon reviewing the relevant methodological literature, it has become apparent that while there are publications available to aid entry-level researchers or individuals without a robust background in signal analysis in using synchronization measurement tools, there is still a lack of comprehension regarding the accuracy and suitability of these methodological approaches for detecting synchronization in signals with distinct characteristics, such as in-phase versus anti-phase signals. Furthermore, our objective was to categorize the phenomenon into dimensions that would assist future researchers in identifying the specific aspects of interest.

The phenomenon of human interpersonal synchronization can be examined from a mathematical perspective by applying the concept of coupled oscillators, which are prevalent in various biological and physical systems. Given that individuals are dynamically coupled, rather than simply aligned, coupled dynamics framework is particularly useful for studying human interactions (Hasson and Frith, 2016), where previous situations experiences and social memory influence the subsequent interaction (Nordham et al., 2018) allowing for physiological (Ferrer and Helm, 2013; Helm et al., 2012)

and behavioral synchronization between people (Loehr and Palmer, 2011; Varni et al., 2020). In this light, a particularly promising avenue of applying the Kuramoto model (Bardy et al., 2020; Calabrese et al., 2021; Néda et al., 2000). The objective is to evaluate commonly used methods for interpersonal synchronization and apply them to time series with varying characteristics, including both in-phase and anti-phase as well as converging and diverging signals. We hypothesize that phase-based analysis will demonstrate superior performance compared to other commonly used methods for measuring synchrony. The rationale behind this hypothesis is twofold. Firstly, phase analysis reflects the phenomenon of interpersonal synchrony as operationalized in physics, where the adjustment of phases is fundamental. Secondly, the hypothesis is reinforced by the observation that phase-based metrics closely align with observers' perception of interpersonal synchrony, in comparison to other commonly used metrics (Novotny and Bente, 2022).

> **Research question № 3**: What methodological principles should be upheld to effectively induce emotions with both high ecological validity and experimental control in research settings?

The stimuli employed to induce emotions in laboratory settings frequently fall short of capturing the profound and genuine emotions experienced in real-life situations, ultimately serving as inadequate reflections compared to real-life counterparts (Levenson, 2003). In essence, the induction method is a "frustrating trade-off between ecological validity and experimental control" (Levenson, 2003, p.217). Various methods are employed in the elicitation of emotions, including the use of specific facial expressions and social interactions (for a comprehensive review of emotion elicitation methods, refer to Fakhrhosseini, M., S. and Myounghoon (2017); Levenson (2003); Siedlecka and Denson (2019); Quigley et al. (2014). Additionally, acting out emotions often results in exaggerated and stereotypical emotional expressions (Castellano et al., 2015), which are rarely observed in naturalistic interactions where emotions are naturally displayed (Sander and Scherer, 2009). Some impressive methods, such as those based on deception, have been employed to induce specific basic emotions. For instance, guilt can be induced by creating a scenario where a participant accidentally collides with a confederate carrying a stack of papers, with the blame either placed on the participant or the confederate (Martin et al., 2010). Similarly, studies on anger and aggression have utilized experiments where participants choose a drink from a selection ranging from unpleasant to pleasant for another participant (Harmon-Jones and Sigelman, 2001). However, systematically inducing *different* emotions in the *same* experimental context, especially across *multiple trials*, can be challenging. In this regard, manipulations of experimental procedures that involve success-failure scenarios have shown particular usefulness

Schuch et al. (2017); Mograbi et al. (2014); Rosi et al. (2019). Consequently, we conducted experiments and assessed the effectiveness of the method in different experimental contexts.

Based on our experimental results, we conclude that our emotion induction method has been effective. In light of this, we can emphasize several principles that mitigated the compromise of experimental control while enhancing ecological validity. First principle: make the induction *believable*. The initial step in developing social psychology experiments involves crafting a compelling cover story that engages participants and diverts their attention from the true purpose of the experiment (Harmon-Jones et al., 2007). In our experiments, participants were informed, based on the cover story, that the objective of the study was to examine how personality traits are exhibited through movements and through interaction between people. Before the experiment, participants completed a personality questionnaire.

Second principle: make the participants *implicated*. This principle serves two purposes. On one hand, it engages participants by ensuring that the assigned task aligns with the cover story. On the other hand, it directs participants' cognitive resources away from the true purpose of the experiment and towards the process of induction itself. These purposes collectively contribute to enhancing the effectiveness of the induction (Nummenmaa and Niemi, 2004, e.g.,). In our experiments, after each trial, we asked participants to rate themselves based on the aesthetic quality of their movement (Publication #2) and the level of synchronization exhibited by each participant with others (Publication #3). This instruction is intentionally designed to be ambiguous. In line with the suggestion by Nummenmaa and Niemi (2004), it is preferable to manipulate task difficulty rather than providing false feedback when inducing emotions. However, in instances where there is no objective measure available to verify the accuracy of the ranking, such as in assessing the beauty of movements, false feedback can also be effective. Moreover, involving participants in the ranking process serves to strengthen the trustworthiness of the cover story. To establish a perception of the authenticity of the success-failure feedback, which was predetermined beforehand and identical for all participants, a preliminary voting test was conducted using Mentimeter. This allowed participants to become familiar with the voting procedure and convinced them that their responses genuinely generated tangible results, as visually displayed through engaging animations on the computer screen to all participants simultaneously via the Mentimeter website.

Third principle: make the induction *relevant*. To ensure the effectiveness of the induction method, it is important for the task to be personally meaningful (i.e., ego-involving) and for success-failure manipulations to hold significance for individuals (Nummenmaa

and Niemi, 2004). While financial incentives based on performance, such as donating $1 or $5, can create relevance (Wiltermuth and Heath, 2009), the choice of task and personalized feedback can also contribute to generating relevancy. On the one hand, obtaining feedback about their ranking position from individuals who share an interest in dancing in a personally relevant task can evoke genuine emotional responses (Publication #2). On the other hand, engaging in a joint task and receiving social comparison feedback that includes their name [NAME, you were the best/worst] can build relevance (Publication #2 and 3), as confirmed by multiple individuals after the experiment, particularly in the case of the intentional synchronization task (Publication #3).

Our emotion induction method and experimental design were carefully developed based on the three aforementioned principles. Additionally, we utilized an image from the OASIS affective picture set Kurdi et al. (2017) as a cue to enhance the induction process and to associate specific success-failure manipulations with particular images, thereby facilitating prompt processing. Moreover, our approach is that negative emotion induction, as indicated by pleasure ratings on the Self-Assessment Manikin scale Bradley and Lang (1994), should not inevitably lead to negative valence (e.g., -4 to -1 – negative; -1 to 1 – neutral; 1 to 4 – positive). Instead, we propose that negative emotion induction should introduce the dynamic reduction of an individual's valence, which was observed in our experiments. Importantly, such valence trends can only be discerned through the use of repeated measures designs. Finally, the lack of substantial impact in the arousal dimension in both experiments can be regarded positively since it prevents the accumulation of heightened emotional intensities and eliminates the possibility of excitation transfer (Zillmann, 1991).

> **Research question № 4**: Do emotions influence interpersonal synchronization within an unstructured and structured experimental context?

By extending the discussion presented in publications 2 and 3, we further develop and integrate the two findings to offer a comprehensive perspective. The outcomes from the experimental theme of this dissertation provide evidence that emotions impact interpersonal synchronization in both unstructured and structured experimental contexts. In particular, our hypothesis posited that inducing positive emotions would lead to enhanced synchronization scores while inducing negative emotions would result in a decline in scores. Overall, the results consistently aligned with our hypotheses. Across all synchronization levels (i.e., Q1, Q2, Q3) and both experimental tasks (i.e., spontaneous hand synchronization and intentional finger synchronization), the Time-In-Sync metric demonstrated an overarching trend. Specifically, negative emotions resulted in the lowest synchronization scores, the neutral state had higher scores, and positive emo-

tions yielded the highest scores. Although not all pairwise statistics were significant, the overarching pattern of the data supports our hypothesis, indicating that positive emotion inductions tend to promote synchronization while negative emotions disrupt it, even when accounting for variations in motivation. Crucially, the effect disappears in pseudosynchrony check. By contrast, the Time-To-Sync metric does not offer definitive evidence regarding interpersonal synchronization dynamics, even though it shows significance in certain pairwise comparisons, the lack of a clear overarching trend suggests that it may indicate somewhat spurious relationships. It is also plausible that with greater variations in motivations, such as an explicit or implicit desire to undermine the interaction as a result of negative emotion induction, this metric would have been more pronounced. However, the absence of changes in motivations proves advantageous in interpreting the scores for the Time-In-Sync metric, as it would have been unclear whether the observed effect is attributable to variations in motivations, emotions, or both. Notably, the magnitude of the effects on Time-In-Sync exhibited variability across different experimental contexts.

Through the experimental procedure conducted across various contextual variations, we had the opportunity to examine the presence of a negativity bias (Rozin and Royzman, 2001), indicating the tendency of individuals to be more susceptible to experiencing negative emotions rather than positive ones. If that were the case, we would expect both sets of results to demonstrate a stronger negative effect. However, the data indicates that the context likely acts as a moderating factor in this interaction. In the unstructured improvisation experimental task (Publication #2), it was observed that negative emotions had a comparable effect to the neutral state induction, whereas positive emotions significantly increased the duration of synchrony among participants. However, in the structured air finger-tapping task (Publication #3), negative emotions exhibited increased efficacy and a more prominent disruptive effect on interpersonal synchronization, while the neutral state yielded outcomes that were comparable to positive inductions but lower in magnitude. These findings challenge previous literature on emotion induction, which suggests that humans are more inclined and readily susceptible to experiencing negative emotions compared to positive ones (Gerrards-Hesse et al., 1994). The results suggest that when individuals are in the presence of others and engaged in interactive tasks, as was the case in the unstructured task, the improvisational nature of the activity may mitigate the negative consequences associated with the induction of negative emotions through experienced togetherness (Himberg et al., 2018; Noy et al., 2015). These findings highlight the importance of context in understanding the negativity bias, demonstrating that structured tasks have the potential to reveal or amplify the effects of negative emotions, while improvisational activities help alleviate them.

Taken together, behavioral findings empirically confirm the research agenda that emo-

tions possess morphogenic properties (Butler, 2011). In essence, this means that the sensorimotor interaction among individuals establishes a social system governed by dynamical systems principles. One fundamental principle is self-organization through coordination patterns, where emotions drive and change the shapes of the system. Thus, the term ”morphogenic” is used to capture the idea of emotions acting as forces instigating changes in the structure and dynamics of the system.

In this dissertation, our multimodal approach incorporated not only behavioral but also cardiac activity. The results from the unstructured setting, specifically the improvisational task, did not provide confirmation of physiological synchronization in the cardiac rhythms. The involvement of gross muscles in movement production increases the metabolic demand of the body, leading to alterations in the functioning of the heart. This interference in the signal introduces additional complexity when trying to discern emotions based on cardiac activity (Brouwer et al., 2018). Consequently, the increased complexity of the cardiac signal could potentially account for the absence of the results observed in our first experiment. To address the interference caused by movement, we tested a structured experimental context where participants were seated, allowing us to investigate the potential impact of systematically induced emotional states on group physiological synchronization. Even in the second and more controlled experiment, where participants remained seated under the supervision of an experimenter and only moved their index fingers, thus having minimal influence on the cardiac rhythm, we did not observe any significant findings in the physiological measures of synchronization.

One possible explanation for this could be that the duration of the trial was insufficient to capture physiological responses. It has been observed in studies like Konvalinka et al. (2011) that certain effects may manifest over extended periods of time, such as half an hour. However, it is worth noting that effects can still be observed even within shorter periods of time. For instance, Gates et al. (2015) utilized epochs of 32 seconds, and Tschacher and Meier (2020) examined 15-second intervals during patient-therapist interventions. Additionally, Behrens et al. (2020) provided insights into the physiological boundaries that impose limitations on dynamics of cardiac rhythms in detecting emotional responses. Specifically, the initial response tends to occur within the first 4 seconds following the presentation of the stimulus, while the duration of a response to the stimuli typically ranges from approximately 5 to 8 seconds. Hence, the duration of the 20-second trials in our second study was suited to the specific context of changes in cardiac rhythms.

An alternative explanation could be that the induction procedure did not directly result in a tendency to synchronize cardiac activity among individuals. While it is proposed that physiological synchronization should not be universally regarded as a proxy for

shared emotions (Fusaroli et al., 2015), it is a robust phenomenon that has recently been observed across various modalities (Ardizzi et al., 2020; Baranowski-Pinto et al., 2022; Czepiel et al., 2021; Kazi et al., 2021; Lange et al., 2022). Furthermore, considering our literature review and the potential reinforcing effect of distress and negative emotions on interpersonal physiological synchronization, as evidenced by studies involving romantic couples experiencing negative emotions, it is plausible to speculate that interpersonal synchronization may be contingent on other factors. Moreover, since emotional responses involve synchronized and multimodal reorganization of organismic subsystems (Scherer, 2005), it is possible that emotions do not directly impact physiological activity and attunement between individuals, but rather influence the delicate interaction between the organismic subsystems. Taking this perspective into account, a holistic analysis that recognizes the whole as greater than the sum of its parts could provide insights into the interplay between various biological rhythms and enhance our understanding of how and why people tick together in time.

10.2 Theoretical and applied implications

The implications of this work extend to both theoretical and practical domains, encompassing a range of potential impacts and applications. Here we address what we believe are key broader implications of this research.

A number of theoretical implications stem from the work conducted in this dissertation. First, Schmidt et al. (1990) suggested that the greatest theoretical challenge in ecological psychology, which investigates the inseparable relationship between individuals and their environment through direct perception, was to create a complete theory of informational interactions. In this dissertation, we emphasized the significance of emotions as relevance detectors (Sander et al., 2003) and as emergent phenomena that arise from an agent's moods, personality, preferences, motivations, and past experiences, among others (Scherer, 2009). From this perspective, emotions play a crucial role in the deployment of successful perception-action interactions, by monitoring an agent's subjective relevance in its environment, thereby encompassing a broad range of informational exchanges. Therefore, the agent's relevance can be viewed as a control parameter that triggers phase transitions in an interaction. Specifically, when the relevance is fulfilled, the agent's stable state represents *morphostasis*, maintaining equilibrium. However, as the discrepancy between relevance and circumstances increases, a phase shift occurs towards the stable state of *morphogenesis*, reflecting the driving force for transformational change in the environment (Butler, 2011). In this light, incorporating emotions as detectors of relevance can be a part of the solution to the challenge. A second theoretical implication highlights that beyond detecting emotional movement qualities (e.g.,

Bianchi-Berthouze and Kleinsmith, 2015; Dael et al., 2012; de Gelder et al., 2010; Noroozi et al., 2019; Roether et al., 2009), the significant challenge in the long term is to accurately determine the stable states of agents through computational methods. This involves recognizing the action, categorizing its meaning, and deciphering the underlying intention as essential steps toward uncovering and identifying emotions. Third, we hope that this dissertation will provide an impetus for further establishing the modality-specific approaches in assessing the dynamics of interpersonal synchronization.

In terms of practical implications, the applications range from the creation of emotion-aware devices to enhancing interactions in real-world contexts. The fifth industrial revolution emphasizes the importance of personalizing AI to meet individual needs, including emotion recognition (Yamin et al., 2022). Furthermore, as robots become integrated into social contexts, they may need to not only decode human emotions but also learn to encode emotions in their expressions, enabling them to attune to individuals (Fischer, 2019). Technological advancements also have various other applications such as assisting in healthy aging (Mieleszczenko-Kowszewicz et al., 2022), facilitating learning (Muñoz et al., 2020)(Eliam, 2019), and improving well-being and quality of life (Zhou et al., 2009). An additional application is with individuals suffering from social deficits such as Autism Spectrum Disorder (Manders et al., 2021) and facilitating clinical interventions that encourage shared positive emotions through congruent rhythmical behavior to foster empathy Behrends et al. (2012) and rapport (Fuchs and Koch, 2014). Finally, interpersonal synchronization plays a crucial role in establishing and maintaining a therapeutic alliance, which is vital for effective therapy outcomes (Koole et al., 2020).

10.3 Limitations of this dissertation

While this dissertation presents valuable insights, to ensure a comprehensive understanding of the scope of our work and pave the way for future research endeavors, it is essential to acknowledge the limitations and constraints encountered throughout the research process.

How intentions to synchronize modify the influence of emotions on interpersonal synchronization remains uncertain

The titles of our two experimental articles report the effects of emotions on spontaneous and intentional interpersonal synchronization. This distinction, also referred to as emergent and planned coordination, or intentional and unintentional coordination, has been previously discussed (e.g., Knoblich et al., 2011; Richardson et al., 2007). The title of

the first experimental article (publication #2) highlights the dominant effect of positive emotions, which fostered synchronization in the spontaneous task. Conversely, the title of the second experimental article (publication #3) indicates that negative emotions disrupted synchronization in the intentional task. Consequently, it can be inferred that the variations in the effects are due to the differences in the levels of intentionality. However, since the experimental task and instructions differed, we are unable to provide conclusive evidence on how naturalistically induced emotions impact the interpersonal synchronization of different levels of intentionality.

Unaccounted changes in pairwise coupling dynamics during group trials

Undeniably, group experimental contexts offer substantial improvements and surpass dyadic interactions in terms of the ecological validity of interpersonal dynamics (e.g., Dale et al., 2020; Himberg et al., 2018; Tomashin et al., 2022). In this light, the principle of self-organization governs social interactions, as well as many other natural systems. It guides the emergence of order in space and time without centralized control through an exchange of energy or information Marsh et al. (2009), much like the coupling observed in Huygens's pendulum clocks. Within our experimental contexts, the coupling between three individuals was not fixed and unchanging but rather fluid and dynamically evolving throughout the trials and the process of order emergence. From this perspective, it becomes valuable to explore the developing dynamics of coupling and uncoupling between pairs of participants (Dumas et al., 2011; Mayo and Gordon, 2020). While the analysis of the Kuramoto order parameter is particularly beneficial in quantifying the self-organization of the group, the dynamics of coupling between pairs of participants remained somewhat elusive. To gain a more comprehensive understanding of the emergence of order, a focused investigation on the intermittent and fluctuating nature of connections between pairs of participants, such as through the analysis of their gaze directions, could have provided valuable insights. To further emphasize this point, during post-experiment discussions after the intentional synchronization experiment, some participants reported challenges in choosing whom to synchronize with, despite the constant presence of both other participants' finger oscillations within their field of view.

The same experimenter performed emotion inductions in both experiments

The experimenter responsible for conducting both experiments played multiple roles, including explaining the cover story, giving instructions, and eliciting specific positive and negative emotions by providing feedback using the Mentimeter platform. However,

Holman et al. (2015) cautioned about the impact of "experimenter effects" where the expectations of the experimenter could potentially compromise the internal validity of the experiments. The authors advocated for the adoption of blind experimental protocols as a means to ensure validity and objectivity in the implementation and interpretation of the experimental results. In this light, double-blind experimental procedures are desirable, in which neither the participants nor the experimenter are aware of the experimental conditions. However, the induction of emotions requires some level of participant appraisal, without which the induction process is challenging (Lazarus, 1991). Conversely, employing an emotion induction method with Mentimeter, where feedback is provided without the direct participation of the experimenter (as demonstrated to the participants), could reduce the reliance on the experimenter and potentially enhance the objectivity of the results. Moreover, the repeated-measures design enables control over internal validity across different experimental conditions by facilitating the control of extraneous variables, such as the "experimenter effects".

10.4 Future perspectives

The limitations identified in this dissertation have provided a foundation for proposing future perspectives. Within this subsection, we outline a range of short-term and long-term suggestions aimed at addressing the identified limitations and enhancing the quality of our current work. By implementing these suggestions, we can refine and improve our research both in the immediate future and in the long run.

Short-term perspectives

First, to ensure a direct and undiluted influence of different levels of intentionality to synchronize emotional responses, it is necessary to conduct a more controlled experiment. In the experiment, participants would be exposed to situations where they engage in both spontaneous and intentional interpersonal synchronization contexts. The challenge lies in developing a cover story and emotion induction method that can be effectively applied in both contexts while maintaining a high degree of similarity. This would facilitate comparative analysis, providing valuable insights into the distinct contributions of intentionality on emotional response and its effect on interpersonal synchronization that will deepen our understanding of human coordination abilities.

Second, to account for changes in pairwise coupling dynamics during group trials, incorporating an eye-tracker within the experimental settings would enable the examination of fine-grained coupling dynamics. The investigation should encompass various timescales, including the observation of intermittent coupling of movements at shorter sub-movement timescales (e.g., Tomassini et al., 2022). Considering coupling dynamics is particularly important, as it enables not only to comprehend the physical aspects

of pairwise connections but also it plays a pivotal role in tackling the current challenge in affective science research. Specifically, instead of solely focusing on affective outcomes, it is essential to explore the temporal evolution of these dynamics over time (Hamaker et al., 2015).

Third, to mitigate the influence of "experimenter effects", it is recommended to evaluate the emotion induction method with the involvement of another experimenter. Moreover, it is crucial to develop a specific induction method (i.e., building upon the Mentimeter induction procedure) and implement a single-blinded research protocol. In this scenario, blinding can only be accomplished for the experimenter, as participants should be able to appraise the experimental conditions to elicit a reaction. Blinding the experimenter can be of crucial importance, as highlighted by Rennung and Göritz (2016) in their meta-analysis, because it has a moderating effect on the prosocial outcomes of interpersonal synchrony, with unblinded experimental procedures yielding statistically weaker results.

Long-term perspectives

First, it is important to delineate the essential components necessary for successfully implementing success-failure manipulations(Nummenmaa and Niemi, 2004). For instance, to understand the additive value of incorporating pictures in the induction procedure, it is essential to conduct separate tests for both the success-failure manipulation alone and the same manipulation combined with validated pictures, enabling the examination of whether the effects persist even in the absence of the image. To further investigate the effectiveness of the induction method, an alternative accompanying stimulus can be employed. Instead of using an image, a negatively valenced sound can be utilized, and its impact on inducing emotions can be tested to determine if the induction is successful to the same extent. The primary concern focuses on making the feedback meaningful to the participants, as in the context of musicians, where feedback in the form of sounds representing incorrect musical chords would generally hold greater negative significance than feedback accompanied solely by visual images. Alternatively, the consideration could be centered around experimentally manipulating the complexity of the task rather than predetermined feedback.

Second, it is essential to move beyond conducting purely laboratory experiments and consider additional settings promoting particular relevance for the participants involved. Going beyond the laboratory settings allows for incorporating real-world scenarios, triggering more authentic participants' experiences. Some examples include participation in collective rituals (Fischer et al., 2014), live music (Chabin et al., 2022) and live dance performances Vicary et al. (2017) as well as naturalistic social (Kinreich et al., 2017) and classroom interactions (Dikker et al., 2017).

Third, develop modality-specific synchronization measurement techniques. The results of the second experiment, when individuals were seated indicated the Kuramoto order parameter values of much higher order of magnitude for behavioral rather than physiological data. This may be an indication that the physiological constraints can be more adapted to studying behavioral rather than physiological data. Nevertheless, a mere sharing of physical space is not enough for experiencing interpersonal synchronization.

10.5 Conclusion

Within the larger framework of social neuroscience, this dissertation primarily revolves around the exploration and comprehension of human emotions by closely examining their action tendencies within the context of interpersonal synchronization. The investigation extends across various sensorimotor modalities (i.e., behavior and physiology) to gain deeper insights into the dynamics of emotional expression and its impact on social interactions. Through its theoretical and methodological advancements, the empirical findings of this study demonstrate the morphogenic properties of emotions in relation to multi-person behavioral synchronization. However, the results also indicate the absence of interpersonal synchronization in cardiac activity. From a theoretical perspective, this dissertation makes a significant contribution to advancing our comprehension of the role of emotions in joint action. It also aims to fill a gap in the current literature by exploring stable state patterns (i.e., morphogenesis and morphostatis) that elucidate the phase transitions within the dynamics of social systems. From a practical perspective, the findings and insights of this dissertation have broad applications across various domains. These applications span from the development of emotion-aware artificial intelligence, which is poised to shape the advancements of the fifth industrial revolution, to enhancing real-life scenarios such as promoting healthy aging, facilitating learning processes, and fostering mental and physical well-being.

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