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PHYSIOLOGICAL SYNCHRONY AND AFFECTIVE PROTOSOCIAL DYNAMICS

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DOCTORAL DISSERTATION

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ABSTRACT

Psychophysiology is a method of measuring physiological signals, such as heart rate or brain waves, and making psychological inferences based on them. The joint changes of physiological signals within a dyad – physiological synchrony – can also be assessed. In previous studies, synchrony measures have been linked to various affective and social phenomena such as empathy or team performance, but a solid connection to background theory is still missing. This work aims to contribute to the collective effort by exploring physiological synchrony and the associated psychological constructs from the perspective of two overarching research questions: "What social dynamics affect physiological synchrony?" and "Is synchrony associated with self-reported empathy and social presence?". The focus of this work is on providing insight into the possibilities of using physiological synchrony measures to assess protosocial affective processes.

The original studies of this thesis include Study I, a theoretical contribution that outlines the core ideas, and four empirical contributions, Studies II-V, that use dyadic psychophysiological measurements and self-reports to examine social dynamics in the context of digital media experience. Study II examined physiological synchrony and social presence in a group movie-watching context and whether chat or biofeedback displays, and physical co-location had an effect. Study III investigated multiple modes of competition and collaboration and their within-dyad effects when playing a digital asynchronous turn-based multiplayer game. Studies IV and V are reports from the same experiment that examined compassion meditation in a shared virtual reality environment by using dyadic synchrony biofeedback to support empathy.

In all studies, heart rate-based synchrony indices were associated with social presence or empathy self-reports, but no similar association was found with electrodermal activity indices. Varying physical co-location also affected physiological synchrony, but changes in social dynamics, e.g. different competition modes, did not. The role of attention rose as a central factor in all studies when interpreting the results; it seems that disturbance-free strict focus on the partner or on the communication channel providing important social information resulted in higher synchrony, whereas any division of attention between separate targets weakened it.

In general, the effect sizes in these studies were mostly rather modest, and the results not entirely systematic. They support the notion that physiological synchrony and social presence or empathy are connected, and a more general link to affective protosocial processes is suggested. The potential for dyadic synchrony measures is theoretically immense, but its complexity is a serious hindrance when trying to harness it in practice.

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Emäsalo, July 2020

Simo Järvelä

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original publications, referred to in the text by their Roman numerals:

I Ekman, I., Chanel, G., Järvelä, S., Kivikangas, J. M., Salminen, M., & Ravaja, N. (2012). Social interaction in games: Measuring physiological linkage and social presence. *Simulation & Gaming, 43*(3), 321–338. http://doi.org/10.1177/1046878111422121

II Järvelä, S., Kätsyri, J., Ravaja, N., Chanel, G., & Henttonen, P. (2016). Intragroup emotions: Physiological linkage and social presence. *Frontiers in Psychology, 7*. http://doi.org/10.3389/fpsyg.2016.00105

III Järvelä, S., Kivikangas, J. M., Kätsyri, J., & Ravaja, N. (2013). Physiological linkage of dyadic gaming experience. *Simulation & Gaming, 45*(1), 24–40. http://doi.org/10.1177/1046878113513080

IV Salminen, M., Järvelä, S., Ruonala, A., Harjunen, V., Jacucci, G., Hamari, J., & Ravaja, N. (2019). Evoking physiological synchrony and empathy using social VR with biofeedback. *IEEE Transactions on Affective Computing, 1*–1. https://doi.org/10.1109/TAFFC.2019.2958657

V Järvelä, S., Cowley, B., Salminen, M., Jacucci, G., & Ravaja, N. (Nd). Augmenting virtual reality meditation: Shared dyadic neurofeedback increases social presence. *Manuscript submitted for publication.*

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ABBREVIATIONS

AI	artificial intelligence
ANOVA	analysis of variance
ANS	autonomous nervous system
BEES	balanced emotional empathy scale
EASI	emotions as social information
ECG	electrocardiogram
EDA	electrodermal activity
EEG	electroencephalography
FA	frontal asymmetry
fEMG	facial electromyography
fMRI	functional magnetic resonance imaging
HF	high frequency
HR	heart rate
HRV	heart rate variability
IBI	interbeat interval
ISS	intersubjective symmetry
LMM	linear mixed model
PVP	player-vs-player
RESP	respiration
RMSSD	root mean square of successive differences
SAM	self-assessment manikin
SCR	skin conductance response
SPGQ	social presence in gaming questionnaire
SPI	social presence inventory
VR	virtual reality
VRE	virtual reality environment

1 INTRODUCTION

This work was born out of three intersecting tech-driven trends: 1) digital media in its various forms becoming the modern frontier of social interaction, 2) constant measuring of biosignals with ubiquitous wearables, and 3) the rise of dyadic neuroscience. Psychophysiology – measuring biosignals to assess psychological phenomena – has already been successfully established as a method to study digital media (cf. Ravaja, 2004), and now that research methods and advances in technology enable studying two or more persons simultaneously, the next logical step is to study social dynamics related to digital media instead of a single person's reactions to it.

Digital media itself has evolved and become more and more interactive – compared with e.g. traditional films – and forms such as digital games, multiplayer online digital games, and virtual environments using virtual reality (VR) technology keep increasing in popularity at a tremendous pace. Wearables and the quantified-self phenomenon (Lupton, 2016) – the trend of constant self-monitoring and measurement with wearables to promote well-being and efficiency – have popularized biosignal measurement and in a rather short time period the possibilities have expanded from mere pedometers and pulse measurement for joggers to a large array of signals and far more advanced algorithmic analysis of those signals. These days, consumers can assess e.g. their stress levels with heart rate variability measures, sleep quality, arousal levels, etc., with activity bracelets and other devices from various manufacturers (Peake et al., 2018). What was previously limited to laboratory conditions and required both expensive specialist equipment and years of expertise, is now available to consumers much more easily. The current generation of devices promises algorithms that crunch the data into easily interpretable indices on personal well-being.

While this development opens up new possibilities also for research, these devices are rarely independently validated and a certain scepticism regarding their validity and reliability is warranted (Peake et al., 2018). Despite biosignal measurement and computational processing becoming increasingly rapid and simple, the fundamental issues of psychophysiology (see below) remain a serious challenge. And, considering the added complexity and how little it has been studied so far, these challenges are even greater when venturing to the realms of dyadic psychophysiology.

The articles in this thesis consist of studies where physiological synchrony – the joint changes of physiological signals between individuals – has been measured with psychophysiological methods while interacting with digital media. As is typical in psychophysiological laboratory experiments, an array of self-reports have been collected after each condition not only to provide a broader scope of measures on media experience, but also to have an assortment of dependent variables with which to compare the degree of physiological synchrony. Study I outlines the basic theoretical tenets that are then explored experimentally in Studies II-V. Study II examines synchrony while watching a selection of movie clips and using a second screen for text-based communication while doing so, Study III focuses on synchrony while playing a digital game with different competitive and collaborative setups, and Studies IV and V explore how physiological synchrony biofeedback can be used in augmenting empathy when performing compassion meditation in a shared virtual environment. While physiological synchrony and its psychological correlates are the underlying themes in the articles included in this thesis, the experiments themselves include many manipulations – such as the presence of AI agent, competition modes, sharing the same physical space, differently valenced stimuli, biofeedback, etc. – that also have effects of their own.

The purpose of this work was to examine which social dynamics affect physiological synchrony and the potential of using physiological synchrony measures in assessing protosocial affective processes such as empathy and social presence (see Section 3.2). A number of self-reports exist for measuring both, but they naturally possess the same challenges inherent in all self-reports (e.g. various biases such as social desirability response bias [van de Mortel, 2008]), and here we aim to achieve the same benefits offered by psychophysiological methods in general (see below) while studying empathy and social presence. The development of physiological synchrony as a method enables its use in studying social interaction in dyadic or small group settings more efficiently and precisely in the future, with potential use in many scientific fields investigating various forms of social interaction and dynamics. As digital media is a tech-driven field, novel technical solutions are always potentially applicable, and in this case, the possibility of using online real-time dyadic synchrony biofeedback to augment digital environments and the social interaction that takes place in them is the more pragmatic level of implications contained within this work. Through real-time analysis of interpersonal relations and biofeedback, it is possible to make these environments, where such a large proportion of daily social contact takes place for many people, a more humane, empathic, softer place.

2 THE PSYCHOPHYSIOLOGICAL METHOD

Psychophysiology is a method of assessing psychological phenomena – such as emotions, attention, or arousal – from physiological signals (Cacioppo et al., 2000). It has also been used in studying peoples' cognitive and affective processes while interacting with various forms of media (Ravaja, 2004), including movies, newspapers, and digital games. A variety of physiological signals can be measured, such as facial electromyography (fEMG), electrodermal activity (EDA), electrocardiogram (ECG), or electroencephalography (EEG), and typically more than one signal is measured simultaneously. A central challenge in psychophysiology, and the reason why commonly demanding experimental setups are required to use the method, is the many-to-many relation of physiological signals and psychological phenomena – i.e. psychological constructs are associated with more than one physiological signal, and physiological signals are associated with more than one psychological construct (Cacioppo et al., 2000; Cowley et al., 2016). Physiological signals can also be used for biofeedback, which in general means visualizing, sonifying or in some other manner providing information to the user on their physiological signals. Traditionally biofeedback has been employed in a clinical context (Schwartz & Andrasik, 2017), but increasingly often it is used in the fields of affective computing (Picard, 2000) and physiological computing (cf. Kosunen, 2018) and to augment interactions in mediated communication and numerous other purposes.

The central benefits of psychophysiology as a research method include high temporal resolution, the option for both phasic event-related analysis and tonic analysis over longer time periods enabled by continuous signal measurement, and a large degree of immunity to various biases, such as social desirability, that affect other measures (e.g. self-reports) since many of the signals are very hard to consciously manipulate without considerable expertise. Additionally, psychophysiology is a highly sensitive method that can measure physiological changes that are otherwise far below the normal level of conscious recognition both in duration and in amplitude. Depending on the measured signal, psychophysiological measures can be also used without interrupting natural behaviour, which can be a considerable boon when studying social interaction and digital media. The complexities of psychophysiology – such as the many-to-many relation between physiological signals and psychological constructs, the wide range of individual differences in signal levels, and requirements for rigorous experimental setups and data processing – are evident in both methodological challenges present in published papers utilizing it to study digital media (e.g. Kivikangas et al., 2011) and the prevalence of contradictory associations between different signals and theoretical constructs (Kreibig, 2010). These challenges highlight the necessity of properly designed experiments and a strong theory-driven approach to research, as more exploratory setups and post-hoc explanations leave so much space for arbitrary interpretations.

3 PHYSIOLOGICAL SYNCHRONY

While psychophysiology has traditionally focused primarily on individual-level measurements and assessments of psychological phenomena, measuring two or more people simultaneously and using dyadic data analysis enable expanding the method to pairs and small groups. Here, the possibility of analysing the concurrent changes in measured signals emerges. The idea itself is not novel; in fact, it has been presented already several decades ago (DiMascio et al., 1957). However, physiological synchrony remains a rather obscure and scantily researched area. Nevertheless, the method has been used to study e.g. therapist and patient relations (DiMascio et al., 1957; Kleinbub, 2017; Marci et al., 2007; Marci & Orr, 2006), marital/romantic interactions (Levenson & Gottman, 1983; Reed et al., 2013), empathy (Levenson & Ruef, 1997, 1992; Marci et al., 2007; Soto & Levenson, 2009), team performance (Ahonen et al., 2016, 2018; Elkins et al., 2009; Fusaroli et al., 2016; Henning et al., 2001, 2009; Henning & Korbelak, 2005; Strang et al., 2014; van Laar, 2019), trust (Mitkidis et al., 2015; Montague et al., 2014), and digital gaming (Chanel et al., 2012). Motor synchrony and mimicry of physical movements and other forms of behavioural synchrony are other closely related forms of synchrony, but this thesis focuses primarily on the synchrony of autonomous nervous system (ANS) signals. Similarly, while some of the original studies of this thesis utilized EEG, as these studies did not involve e.g. fMRI-based hyperscanning (Czeszumski et al., 2020; Hari et al., 2015; Hari & Kujala, 2009; Nummenmaa et al., 2018), the brain-to-brain synchrony assessed with those brain imaging techniques is beyond the scope of this thesis.

Over the years, different terminology with varying definitions has been applied to describe this phenomenon. At least physiological synchrony, linkage, coherence, coupling, convergence, concordance, interpersonal autonomic physiology, hyperscanning, and interpersonal physiology are used in the literature. The field is not yet unified to the degree where established definitions for these terms or their differences exist; for a recent review see Palumbo et al. (2016). In this thesis, I do not make a distinction between most of the terms listed above or go into minute detail of their varying definitions. Here, I use convergence to refer to the psychological level of assessment and physiological synchrony to refer to the signal level, and generally refer to synchrony indices regardless of exactly how they are calculated from physiological signals. For example, using this terminology, you could say that emotional convergence can be assessed from physiological synchrony indices.

Numerous methods of calculating physiological synchrony indices from various physiological signals exist (Palumbo et al., 2016). The core idea is to quantify the joint changes of the signals of two or more persons somehow in either time or frequency domain depending on the physiological signal and its properties. A common method for this is simply calculating a Pearson correlation between the signals, but other measures such as cross-correlation and coherence are also often used. More complex methods, such as dynamic correlation (Liu et al., 2016), have been developed to counter some challenges related to analysing these indices (e.g. the autoregression that is typical for physiological signals over time), but an extensive review of the methodology is again beyond the scope of this work.

Currently, no singular theoretical model for physiological synchrony with strong empirical support exists (Palumbo et al., 2016), and considerably more well-conducted empirical studies to test different theoretical assumptions are needed before that is possible. The three main broad questions that the field needs to tackle are the following:

- How should synchrony indices be analysed from each signal?
- What are the theoretical psychological constructs associated with synchrony?
- How and why does convergence occur between individuals, i.e. what are the brain processes causing convergence?

This thesis mainly addresses the second question.

3.1 TWO PATHWAYS TO PHYSIOLOGICAL SYNCHRONY

Conceptually, five distinct types of physiological synchrony (see Figure 1) can be separated (Nummenmaa et al., 2018). A strong cause of synchrony between individuals often is simply that they react in a similar manner to the same stimuli (e.g. the participants are watching the same movie). In other words, the individuals react to something external which is not related to the social dynamics of the individuals or which does not require a specific brain process that would synchronize physiology between individuals as such. While relevant in some cases, often in laboratory experiments, such sources of synchrony need to be controlled in order to study other types of synchrony (c-e) as the indices themselves tend to be blind to the possible causes.

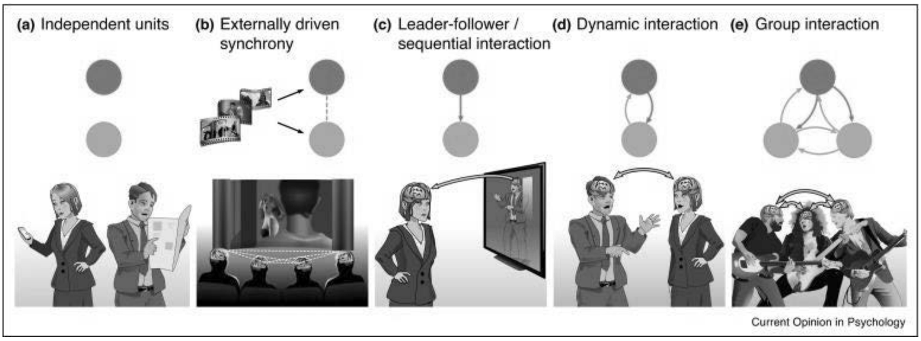


Figure 1 The five types of physiological synchrony. Reproduced with permission of the copyright holder Elsevier (Nummenmaa et al., 2018).

Bruder and colleagues (2012) suggested that two separate processes for synchrony exist: a bottom-up contagion-based process and a top-down appraisal-based process.

The contagion-based process is the more primitive process that relies on the mirror-neuron system (Rizzolatti et al., 1996; Rizzolatti & Craighero, 2004) to mimic the physiological states of others, e.g. facial expressions (Dimberg & Öhman, 1996; Korb et al., 2014). This mimicry leads to emotional contagion (Barsade, 2002; Hatfield et al., 1993), convergence of emotional states, and physiological synchrony. According to the embodied cognition paradigm (Barsalou, 1999, 2008; Mahon & Caramazza, 2008; Niedenthal, 2007; Niedenthal et al., 2005), the same brain networks are required to understand the emotional states of others as is needed to produce them. This mimicry is required to understand the other person's state (see cognitive empathy and empathic accuracy below), and, in addition, presumably to coordinate group-level survival-related emotional and motivational (i.e. emotiovational) (Roseman, 2013) states on a primitive behavioural guidance level. Recently, Shamay-Tsoory et al. (2019) presented a model for the core neural mechanism of social alignment that consists of a three-component feedback loop of a misalignment detection system, an alignment system, and a reward system. In this model, behavioural synchrony, emotional contagion, and cognitive alignment are all based on the same core primitive herding mechanism and interlinked so that activating one activates the others also to a degree. Plausibly, if all of these share the same core neural mechanisms and are part of the same system, it provides us with the generic framework to examine the associations between complex psychological constructs and physiological synchrony measures.

An appraisal-based process, on the other hand, relies on higher social cognition where an individual appraises the prevailing social context, the position of the other person, the expressions they project, and their behaviour, and forms a shared understanding of the situation, leading to emotional convergence and physiological synchrony (Bruder et al., 2012).

Conceptually, these two paths can be separated, but whether they are functionally and anatomically a single system merely described from a bottom-up or top-down perspective is ultimately an empirical question. Some empirical evidence supporting this model comes from brain imaging studies that have found that the selection of psychological perspective affects synchronous brain activity (Lahnakoski et al., 2014; Nummenmaa et al., 2014). According to the Emotions As Social Information (EASI) model (Van Kleef, 2009, 2010; Van Kleef et al., 2010) the role of emotions as social information is emphasized in ambiguous situations where explicit social information is scarce, thus possibly also emphasizing the role of physiological synchrony. The possibility of an appraisal-based source of synchrony is rather difficult to control in an experimental setting, as otherwise strict setups tend to aim for maximal similarity of environmental and other conditions between subjects, creating a context that is easily appraised by higher social functions.

3.2 ASSOCIATED PSYCHOLOGICAL CONSTRUCTS

In dyadic psychophysiological measurements, the addition of the social interaction component increases the level of complexity considerably. Here social interaction refers to numerous different dynamics and processes that can range from a mere acknowledgement of sharing a similar situation with another person to the possibility of interacting with them, to co-presence in shared space (physical or virtual), and to joint action and all forms of active communication in which human beings engage. Dyadic physiological synchrony and convergence of psychological states can occur throughout this range of social interactivity. This thesis focuses on the early stages in the continuum, where primitive emotional processing prevails and uses the term *protosocial* to refer to it. The level of emotions and other fast behaviour guiding processes of which people are often not fully aware of, is where psychophysiology as a method excels.

As such, assessing emotional states is the traditional area of psychophysiology, and as a method, it requires using some emotion theory framework to interpret the signals. Of the many schools of emotion theory, some are traditionally more suited for psychophysiological inferences than others; basic emotions (Ekman & Cordaro, 2011) and dimensional models (Russell, 1980; Wundt, 1897; Yik et al., 2011) are typically used, and appraisal theories (Scherer, 1999, 2005, 2009) or constructionism (Barrett, 2013) less so. These are also applicable when examining dyadic interactions. In any social setting, the emotional convergence or similarity of emotional states of those present is central, both on a primitive behavioural guidance coordination level and on a higher social cognition level. Thus, simply the question of whether the people in a certain context were experiencing the same emotions might be a relevant one, and something that measuring and analysing physiological synchrony can answer. Individual reactions to controlled stimuli can be assessed with single-person measurements and then compared across individuals, but more complex studies into emotional contagion and synchrony dynamics require dyadic measurements. In addition, high temporal resolution of psychophysiological methods enables analysing also emotional contagion as a process and not just as an state of emotional convergence, that is, whether one person is converging with the other or whether it is a more balanced dynamic (Feldman et al., 2011; Müller & Lindenberger, 2011; Palumbo et al., 2016). Using this methodology to study different social dynamics (e.g. power structures, social roles, contexts) within dyads or small groups at a minute level is a highly promising direction for future research, but first a solid connection from synchrony measures to protosocial affective processes – e.g. social presence and empathy – should be established and then later expanded to cover more complex dynamics.

3.2.1 SOCIAL PRESENCE

The theory of social presence (Biocca et al., 2003; Biocca & Harms, 2003, 2002) examines the levels of social interactivity, and is defined as follows: *"Social presence in a mutual interaction with a perceived entity refers to the degree of initial awareness, allocated attention, the capacity for both content and affective comprehension, and the capacity for both affective and behavioral interdependence with said entity."* (Harms & Biocca, 2004). The theory describes the levels of interactivity and how these contribute to the subjective feeling of being socially connected to another. The theory proposes three levels of social presence: 1) co-presence – the sense of sharing the same space or being in touch with the other person, 2) psychological involvement consisting of bi-directional attention, affective understanding, and affective interdependence (see below), and 3) behavioural interdependence – the sense of being able to affect the other's behaviour and to be affected by theirs. As a subcomponents of psychological involvement, bi-directional attention refers to whether the persons paid attention to one another, affective understanding to how strongly the persons feel that they can understand the affective states of their partner and are being understood themselves, and affective interdependence to how strongly they felt that their affective state depended on the other and vice versa. Together these contribute to the overall sense of social presence. In the Social Presence Inventory (SPI) (Biocca & Harms, 2003), all items are rated bi-directionally, e.g. "I could tell how my partner felt" and "My partner could tell how I felt". Intra- and intersubjective symmetries (whether a single participant's self and other scores were similar, and whether their own ratings and their partner's ratings were similar, respectively) can also be calculated from the bi-directional self-report items, enabling the assessment of whether the sense of social presence was mutually shared and balanced or somehow skewed. Notably, social presence as such is not limited to positive experiences only –

a heated argument would also be rated as having a strong social presence for those participating in it. In this thesis, Study I postulates that physiological synchrony can be used as a measure of social presence, and this notion is examined through empirical Studies II-V.

3.2.2 EMPATHY

Considering how widely studied empathy is and how commonly it is used in describing traits and interpersonal relations, the psychological theories of empathy are surprisingly vague and dispersed with no widely accepted single definition or theoretical framework (Cuff et al., 2016). Probably the most agreed upon aspects of empathy are the understanding of another person's affective state and the convergence of persons' affective states (de Vignemont & Singer, 2006; Decety & Jackson, 2004; Ickes, 1993). The various definitions include many different affective and cognitive processes, and several attempts to combine these various aspects in a single multi-component model have been made (Cuff et al., 2016; Walter, 2012). In this development, empathy theories seem to follow the same path that emotion theories have followed in the past. These multi-component models can be seen as the current psychological view on empathy, and they typically include (with varying terminology used in different studies or models): 1) *cognitive empathy* meaning the ability to recognize the emotional state of someone else, 2) *affective empathy* involving *emotional contagion* and *convergence,* 3) *sympathy* where the affective states are not congruent but the emotional state of the other causes a dissimilar emotional reaction such as compassion, pity or anger, and 4) *empathic behaviour* where the empathy processing leads to concrete behaviour that can be assessed as empathic such as consoling or donating money to those in need. In some models (Janssen, 2012), sympathetic reactions and empathic behaviour are combined as empathic responding, and brain imaging and lesion studies provide support for separating the two processes for cognitive and affective behaviour (Engen & Singer, 2013; Shamay-Tsoory, 2011). The consistent individual differences in the processes form trait-level differences between individuals that are also often referred to when discussing empathy (Banissy et al., 2012; Baron-Cohen & Wheelwright, 2004).

Considering the complexity of empathy as a phenomenon, measuring it is far from simple. Typically, self-reports are used in assessing trait and state empathy, but also tests exist for empathic accuracy, and such empathic behaviour as willingness to help can be observed and tested. As emotional states can be assessed with psychophysiology, it is natural that concurrent emotional states and their congruence can be measured from the physiological synchrony of dyads. Empathy and physiological synchrony have indeed been found to be positively associated in previous studies (Levenson & Gottman, 1983; Levenson & Ruef, 1997, 1992; Soto & Levenson, 2009).

3.2.3 COMMONALITIES BETWEEN EMPATHY AND SOCIAL PRESENCE

While they are not typically discussed together, notable similarities arise when examining the components of social presence and empathy side by side. Particularly, affective understanding and cognitive empathy (see above) appear to be referring to the same capability of recognizing the affective states of others, only with the difference that affective understanding as part of social presence also includes bi-directional mutualness. Similarly, emotional contagion and affective interdependence (see above) both describe a dynamic where a person's affective state is affected by another person's affective state. Empirical evidence on whether they are indeed the same brain functions just described differently in a different theoretical framework would require extensive brain imaging studies. Drawing from the model of Shamay-Tsoory et al. (2019) for core neural mechanisms for social alignment, I propose that these conceptually similar elements in empathy and social presence theories refer to the same brain functions related to protosocial level recognition of other's affective states and processes facilitating the convergence of affective states. Psychophysiology and particularly physiological synchrony have the potential to act as a measure of that shared sector of empathy and social presence that is related to emotional convergence and social alignment dynamics. This idea and the empirical evidence of the relation of physiological synchrony to empathy and social presence are examined in this thesis through research question 2.

4 RESEARCH QUESTIONS

Original Studies I-V investigated physiological synchrony in a variety of experimental settings focusing on different forms of digital media and social interaction. Study I outlined the theoretical approach then examined it in Studies II-V through specific research questions. Study II examined whether social presence and physiological synchrony were connected, and whether physical co-location or two different types of technologically mediated social information (chat and heart rate biofeedback) affected them in the context of group movie watching. Study III's main research questions explored whether a similar connection between social presence and physiological synchrony found in Study I would exist also in the context of asynchronous digital game play and whether different modes of competition or collaboration would affect the amount of synchrony. Studies IV and V had two main research questions: Is physiological synchrony connected to empathy similarly as it was found to be connected to social presence in Studies II and III? and Can empathic connection and social presence be augmented and supported with biofeedback when sharing the same virtual environment?

This thesis summarizes Studies I-V through two overarching thematic research questions:

1. What social dynamics affect physiological synchrony?
2. Is synchrony associated with self-reported empathy and social presence?

These research questions aim at finding common ground in several studies published over the years that had their own specific research questions. The experimental setups included in the articles of this thesis have a shared theme, but vary markedly in details – which is natural considering the variety of forms of digital media as experiment stimuli (cf. Järvelä et al., 2015) and the complexities of dyadic measurements. The central observations from the studies that contribute to the broader discussion on the nature of physiological synchrony, are highlighted and discussed. Specific focus is on the shared commonalities of the findings from each study, and they are summarized through these overarching research questions.

5 METHODS

5.1 PARTICIPANTS

Most participants in all empirical contributions were Finnish university students. The studies had primarily mixed-sex dyads, and the participants signed up as pairs and knew each other beforehand; see Table 1 for a summary. Depending on the study and the analysis, some participants had to be excluded due to technical difficulties.

Table 1. *Summary of participants in Studies II-V.*

	N	Final N	Male	Female	Other	Age range	Age M	Mixed dyads	Friends
Study II	62	52-57	21	41		19-35	24.2	yes	no
Study III	100	82	58	42		18-32	22.9	no	yes
Study IV	78	72	28	44		19-50	26.1	yes	yes
Study V	78		32	45	1	19-50	26.1	yes	yes

5.2 TASKS, PROCEDURES, AND EXPERIMENTAL SETUPS

In Studies II-V, physiological synchrony was examined in the context of various forms of digital media. Study II focused on movie clip watching in small groups, Study III examined various modes of collaboration and cooperation when playing a digital game, and Studies IV and V utilized a shared virtual reality environment for meditation purposes. See Table 2 for a summary.

Table 2. *Summary of stimuli, tasks, and experimental manipulations in Studies II-V.*

	Group size	Conditions	Stimulus / task	Manipulations
Study II	4	4	Movie clip watching	HR biofeedback, chat, co-location
Study III	2	4	Digital game playing	Competition modes (4)
Study IV	2	8	VRE meditation	Solo/shared, EEG biofeedback, respiration biofeedback
Study V	2	8	VRE meditation	Same as Study IV

VRE = virtual reality environment, HR = heart rate

In general, when conducting synchrony experiments, it is essential to be aware that joint actions and shared stimulus easily cause similar physiological reactions and are seen as physiological synchrony within dyads (cf. Figure 1). If the aim is to study physiological synchrony related to other factors – such as social dynamics – joint actions and shared stimuli need to be controlled or it will be impossible to separate the possible causes of synchrony and interpret the results. For this reason, Studies II-V primarily used within-subject designs, asynchronous tasks, and manipulated the social context in various manners when the stimulus itself was shared.

Figure 2 Video stimuli view from Study II, including the HR biofeedback visualization, is shown in panel A, and the chat interface is shown in panel B. Reproduced with permission of the copyright holder (Järvelä et al., 2016).

In Study II, video stimuli were presented to the participants in four-participant groups while augmenting their social interaction by either graphic visualization of heart rate (and their synchrony within the group) or text chat on a mobile device. At the beginning, one physically co-located dyad and one non-co-located dyad were formed at random. The four roughly 6-

minute-long video clips shown were selected so that they represented varying emotional valence (positive/negative) and arousal (high/low). The videos were randomly assigned to the four display conditions: both heart rate and text chat feedback off, heart rate on and chat off, heart rate off and chat on, and both on. The order of conditions was randomized. Text chat allowed reading and writing messages with other participants, and that interaction was encouraged by presenting three questions related to the contents of the current video clip to them. Heart rate visualization displayed the heart rates of all participants within the group and the synchrony between them (correlation of heart rates within a 30s moving window) shown as colour-coded line thickness between participants. After each condition, the participants filled out self-reports.

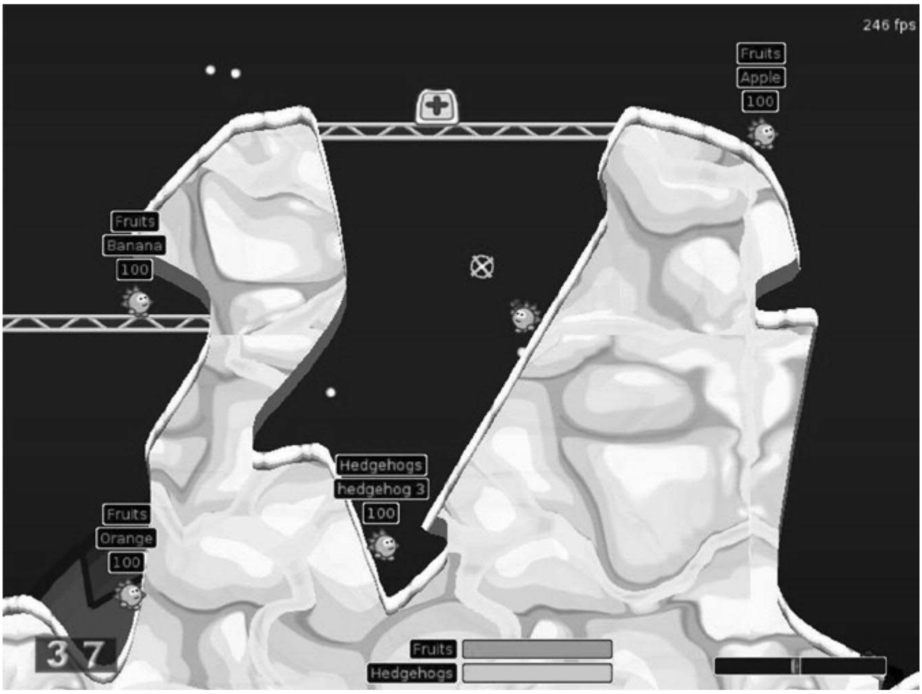


Figure 3 Screenshot from Hedgewars, the game played in Study III. Reproduced with permission of the copyright holder (Järvelä et al., 2013).

In Study III, the dyads played turn-based 2D artillery game Hedgewars (http://www.hedgewars.org) in various competitive and cooperative team modes with artificial intelligence (AI) agents. The gameplay proceeds with intermittent turns of action when it is the participant's turn and watching when it is their partner's turn, providing an asynchronous task for the participants. The different conditions were played in a randomized order, and also the order of player turns was randomized. The four conditions were

1) full cooperation (single team for both players against single AI team), 2) competitive cooperation (two-player teams against two AI teams), 3) competition with AI allies (two-player teams against each other both with an AI ally team on their side), and 4) competition without AI allies (two-player teams against each other, no AI involved).

Figure 4 Virtual environment from the Studies IV and V showcasing respiration- and EEG-based biofeedbacks.

In Studies IV and V, the dyads performed a variation of compassion meditation within a shared VRE that was augmented with different forms of respiration- and brainwave-based bioadaptations. The participants could only interact via the VR environment. The task – to concentrate empathic, warm, and compassionate feelings towards the other participant's avatar, a statue placed opposite them in the VR space – remained the same in all conditions. Participants were encouraged to use the information that the VR provided in their task. The eight conditions in the experiment varied the forms of biofeedback in the VR: respiration and EEG both off, respiration on and EEG off, respiration off and EEG on, both on, and all of these were conducted either with the pair present in the VR or in solo mode. The opposing statue was lit in the dyadic conditions signalling that the avatar was active. The order of conditions was randomized for all dyads. Each condition consisted of a 2-minute baseline period in the VR, a 6.5-minute meditation period, and self-reports that were also filled out in the VR.

5.3 MEASURES

In all empirical contributions, other self-reports besides social presence and those related to empathy were also used – typically e.g. Self-Assessment Manikins (Lang, 1980) for emotional dimensions of valence, arousal and dominance – and details on these can be found in the original publications. Several physiological signals were collected using various devices depending on the experiment, and typically only some of the measured signals were used in calculating synchrony indices or for biofeedback. Table 3 summarizes the measures used that are related to the topic of this thesis; see original publications for more details.

Table 3. *Summary of measures used in Studies II-V.*

	Physiological signals	Self-reports	Other measures
Study II	HR	SPI	
Study III	ECG, EDA	SPGQ, BEES, Perceived Comprehension scale from SPI	
Study IV	EEG, RESP	Empathy	System log files
Study V	ECG, EDA	Empathy, SPI, Valence, Arousal, Dominance	

SPI = Social Presence Inventory, SPGQ = Social Presence in Gaming Questionnaire, BEES = Balanced Emotional Empathy Scale

In Study II, Polar Band heart rate monitors were used in measuring the heart rates of all participants. After each video clip, the participants filled out the SPI (Biocca & Harms, 2003) bi-directionally in relation to both their designated partner and the group as a whole.

In Study III, the physiological signals were measured with Varioport-B portable recorder systems (Becker Meditec, Karlsruhe, Germany). EDA, EMG, EEG, ECG, respiration, and acceleration were measured, and EDA and ECG measures were used in the article included in this thesis. Balanced Emotional Empathy Scale (BEES) (Mehrabian, 1996) was used to measure empathy traits, and also the participant's previous experience with the game (or similar) used in the experiment was collected. After each condition, the participants filled out the Social Presence in Gaming Questionnaire (SPGQ) (de Kort et al., 2007) and the bi-directional Perceived Comprehension scale from SPI (Biocca & Harms, 2003) that was missing from the SPGQ.

In Studies IV and V, the physiological signals EDA, ECG, EEG, and respiration were measured using QuickAmp recorder (BrainProducts GmbH, Germany). The EEG and respiration signals were also used in the bioadaptations of the VRE. After each condition, the participant's self-reported empathy (Batson et al., 1987), and valence, arousal, and dominance using graphic Self-Assessment Manikins (SAM) (Lang, 1980) were measured. In addition, Co-presence, Perceived Affective Interdependence and Perceived Affective Understanding scales from the SPI (Biocca & Harms, 2003) were used. SAM's and social presence items were reported bi-directionally so that intersubjective symmetry (ISS) scores, which measure how accurately the participants assessed each other's emotional states, could be calculated.

5.4 DATA PROCESSING

In Study II, heart rate data from Polar Band devices were pre-processed in Matlab and resampled to 32 Hz. Values three standard deviations from the mean were omitted and replaced with interpolated values. Frequencies below 0.04 Hz were removed, the data smoothed, and the series mean removed from each participant's data. To obtain synchrony indices a ±5 second window was used in calculating cross-correlations for each value. The highest cross-correlation within this window was chosen for the analysis, and Fisher transformation was applied to normalize the distribution.

In Study III, EDA was recorded at a 32 Hz sample rate, downsampled to 4 Hz, and smoothed using the Ledalab toolbox for Matlab. Tonic and phasic components were separated using the nonnegative deconvolution method (Benedek & Kaernbach, 2010a). ECG was recorded at a 512 Hz sample rate and processed with the ECGlab toolbox for Matlab. R-peaks were identified from the original 512 Hz series and corrected for ectopic beats. The interbeat interval (IBI) time series was obtained by interpolating with cubic splines at 4 Hz. The square root of the mean squared difference of successive IBIs (RMSSD) and high-frequency (HF) component of spectral IBI were extracted for heart rate variability (HRV) measures. Synchrony indices were calculated for IBI, HF, RMSSD, and phasic and tonic components of EDA. Frequencies below 0.04 Hz were filtered out and mean square coherence calculated between 0.05 and 1.25 Hz using 256-point Hann windows with 75% overlap, weighted with series power spectral values. Ten-second mean values of IBI and phasic and tonic EDA were calculated, preceding values subtracted from each data point, and cross-correlations calculated, which were then Fisher z-transformed.

Study IV used the system log files of the VR environment for synchrony indices. The system log files included the number of out-breaths during each condition, the number of times the respiration synchronization effect was shown in the VR environment, the average relative EEG frontal asymmetry value, and the number of seconds the EEG synchronization visualization was shown in the VR environment during each condition. The system calculated a frontal asymmetry (FA) value for the bioadaptations from the alpha band at 8-13 Hz, using the formula ln(F3)-ln(F4) in real-time, and then scaled it for each participant for each session by tracking the minimum and maximum values. The EEG FA was calculated with a 9-second moving average, and the synchrony effect was displayed if the participants were both within the same percentage range of their individual ranges. This log file data saved by the system was the data used in Study IV for statistical analysis together with self-reported empathy scores averaged within the dyad.

In Study V, raw EDA was low-pass filtered, downsampled, and smoothed in Ledalab v.3.4.9, and Continuous Decomposition Analysis (Benedek & Kaernbach, 2010b) was used to acquire SCRs for Matlab r2019a. Synchrony indices for each dyad and condition were calculated as the Pearson correlation of both participants' SCR signal dispersion (std dev) within a 40-second moving window with 50% overlap. Statistical significance of synchrony was tested using a permutation approach with the experimental sample as a control, i.e. synchrony of randomly sampled dyads was compared with the true dyads. Colibri package (https://github.com/bwrc/colibri) was used to detect RR peaks and form IBI time series from the raw ECG data, and artefacts were removed. HRV RMSSD was calculated within 60-second sliding windows with a 50% overlap, and Kendall correlations were calculated directly from HRV. Statistical testing was performed similarly to the EDA data. Intersubjective symmetries were calculated for bi-directional self-reports as the absolute difference between participant A's self-scores and participant B's scores for A (i.e. 'for the other'), and then scaled by reducing the score from the scale maximum.

5.5 STATISTICAL ANALYSIS

Complex experimental setups, hierarchical data structures, and the need for dyadic analysis warranted the use of Linear Mixed Models (LMMs) in most studies, as is common for psychophysiological data analysis in general. Study V used a different approach.

5.5.1 STUDY II

Due to the hierarchical nested data structure – participants within dyads within groups – instead of conventional ANOVA type methods, a generalized multilevel modelling procedure that is suitable for dyadic analysis (Kenny et al., 2006) was adopted. Ultimately, LMM with maximum likelihood estimation was used to analyse the data in SPSS 18. For HR data, cross-correlations were calculated for each movie condition, pair identifiers were used as a subject-variable, and movie (four different movies) was specified as the repeated variable. The best fit to the data for the residuals was estimated with -2 log-likelihood function, and based on that, unstructured variance-covariance (UN) structure was selected. A random intercept was specified with groups as the subject variable to account for the hierarchy of pairs within groups. A fixed-effects model with main effects for location (co-located / non-co-located), chat display (on/off), HR rate visualization (on/off) and four different movies was specified, and two-way interactions for location × chat display and location × HR visualization were determined.

For self-reports, the analysis was similar to the HR data analysis described above, except participant identifier was specified as the subject variable and to account for the participant–pair hierarchy a random intercept was defined for the subject pairs. For analysing the associations of self-reported social presence and HR cross-correlations, social presence scores were first averaged over both pairs to obtain a single dyadic score and then grand-mean centred, and then a fixed-effects model that included only a main effect for this covariate was used.

5.5.2 STUDY III

All physiological synchrony indices were averaged over a single condition, i.e. the whole playing period. The dyadic data were both mean and difference aggregated. The four play sessions were aggregated into a single value per dyad, and regular t-tests with z-scores were used in investigating whether synchrony was present. The differences between conditions and the associations between physiological measures and self-reports were analysed with LMMs in SPSS 21. Different models were used in analysing the association of synchrony with other variables. A model with condition, previous experience with the game, interaction, and period length as predictive variables was used when analysing the effects of different conditions. The period length was included in the model since previous studies have suggested that it might have an effect on certain synchrony scores (cf. Henning et al., 2001). Gender and period order were omitted from the final analysis since they did not have a consistent effect in the preliminary analysis. Covariate model that included also condition and period lengths as predictive variables was used to analyse the associations between synchrony indices and self-reports. Previous experience with the game -variable was omitted from the final analysis as it did not have significant effects in preliminary analyses.

5.5.3 STUDY IV

LMM procedure with maximum likelihood estimation was used in analysing the data with SPSS (v. 24). As the within dyad data was correlated and not independent, the analysis was conducted on a dyadic not individual level as recommended by Kenny et al. (2006). In the model, the condition was defined as a fixed effect, within-dyad mean empathy as the dependent variable, dyad ID as the subject variable, and presentation order of the conditions as the repeated variable, and compound symmetry covariance structure was used. Five planned contrast tests were conducted (dyadic vs. solo, EEG vs. no feedback, EEG vs. respiration feedback, respiration vs. no feedback, and both feedbacks vs. no feedback). The effects of synchrony biofeedbacks were analysed with LMM fixed effect model with dyadic mean empathy as the dependent variable, synchrony scores of respiration and EEG as independent variables, condition as a repeated variable, and dyad ID as a subject variable, and compound symmetry covariance structure was used.

5.5.4 STUDY V

For permutation testing, the Pearson correlation matrix was formed with rows of participant A from each dyad, and columns of participant B. The mean of the matrix diagonal is then the group-wise average synchrony value, which gives the 'test measurement'. For testing significance, correlation matrix columns were shuffled to obtain a random sample of pairwise correlations. The permutation test statistic was formed by repeating the random sampling 10000 times to generate a distribution of correlations, and then the real correlation was plotted against that to show the statistical difference between them. P-values were calculated by counting the proportion of permutated mean-differences that were larger than our observed value in the data. This process was repeated for both ECG and EDA data.

For conditions where significant physiological synchrony was observed, an exploratory analysis of the relationship between synchrony indices and self-reported empathy and social presence was conducted. A multiple regression model with all self-report subscales as independent variables and synchrony as the dependent variable was used.

6 RESULTS

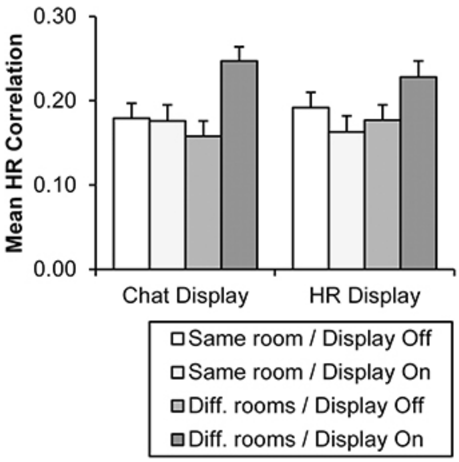
This section presents the main results of this thesis. More detailed results for each experiment can be found in the original research articles. In this section, the results and their interpretation will be discussed briefly in the context of the study in question, and in the General Discussion below the results are summarized in relation to the overarching thematic research questions of this thesis.

6.1 STUDY I

Study I introduced the idea of using dyadic psychophysiology and physiological synchrony to measure aspects of social interaction in games. Social presence was presented as a theoretical framework for interpreting the shared experiences of players, and physiological synchrony is suggested as a way to measure social presence with psychophysiological methods. Study I hypothesized that synchrony measures and the association with social presence provide a way to address many aspects related to social interaction in games, e.g. comparing playing contexts, power dynamics, social roles, and personal preferences towards different types of social dynamics in games. Study I emphasized how the potential observed synchrony ought to be interpreted in that particular context, taking into account the specific nature of digital games as stimuli (Järvelä et al., 2015) and the social interaction and dynamics that take place during gameplay. Study I introduced these ideas, but provided no experimental evidence to support them. Study I outlined most of the questions that Studies II-V later attempted to answer.

6.2 STUDY II RESULTS

Within-dyad HR cross-correlations for different conditions are shown in Graphic 1, displaying the highest HR synchrony when in separate rooms for both the chat and HR biofeedback conditions. In the LMM analysis the main effect for the chat ($F(1, 43.41) = 7.32$, $p = .01$), but not the HR biofeedback ($F(1, 49.86) = 0.38$, $p = .54$), was significant. Also interaction effects between location and both the chat ($F(1, 60.29) = 8.54$, $p = .005$) and the HR biofeedback ($F(1, 60.24) = 5.38$, $p < .05$) were significant.



Graphic 1 Mean HR correlations in Study II. Reproduced with permission of the copyright holder (Järvelä et al., 2016).

The effect for both chat and HR biofeedback was pronounced when the participants were in different rooms compared with when they were in the same room. All subscales of self-reported social presence and HR cross-correlations were positively associated ($p < .05$); see Table 4 for details.

Table 4. *LMM for HR cross-correlations and social presence evaluations.*

	df	*F*	*p*	Parameter estimate	SE
Co-Presence	92.04	5.13	.026*	0.03	0.01
Attentional Engagement	91.48	5.73	.019*	0.04	0.02
Emotional Contagion	83.63	4.73	.032*	0.03	0.01
Comprehension	83.05	7.85	.006**	0.02	0.01
Behavioral Interdependence	86.26	5.30	.024*	0.03	0.01

* p < .05, ** p < .01. Reproduced with permission of the copyright holder (Järvelä et al., 2016)

6.3 STUDY II DISCUSSION

Displaying HR visualization for participants increased dyadic physiological HR synchrony, but only when they were physically located in separate rooms. No such effect was found when the participants were physically co-located. This result suggests that the role of dyadic biofeedback is highlighted when other sources of information are scarce in technologically mediated communication, and perhaps more attention is paid to the few sources of information available, strengthening biofeedback's support for synchrony.

Dyadic mean synchrony was connected to social presence on all subscales, but HR biofeedback did not seem to increase social presence as such – chat seemed clearly more effective in increasing social presence, perhaps due to increased interactivity. Perceived social presence was the strongest with chat and when non-co-located, supporting the idea that increased attention to limited channels strengthens the sense of presence and interactivity, whereas multiple channels and co-location divide the attention.

6.4 STUDY III RESULTS

The t-test results (see Table 5) confirm that on a general level physiological synchrony existed in all conditions, and Cohen's d effect size estimates ranging from 3.38 for IBI z-score to 1.03 for HF z-score indicate strong effect sizes (Cohen, 1992).

Table 5. *Physiological linkage effect of different physiological z-indices.*

	M	SD	*t*	*p*
IBI	1.06	0.63	10.7	< .001
RMSSD	1.16	0.73	10.22	< .001
HF	0.27	0.54	3.28	.002
Tonic EDA	0.87	0.79	7.07	< .001
Phasic EDA	1.33	1.17	7.33	< .001

df = 40, test value = 0, N = 41. Reproduced with permission of the copyright holder (Järvelä et al., 2013).

In the LMM analysis, IBI coherence was associated with the condition main effect (F(3, 115.06) = 4.682, p = .004), with the highest synchrony in the competitive condition with no AI present, and no differences between other conditions. Planned contrasts tests (cooperation vs. competition, competitive cooperation vs. competition with AI, full cooperation vs. competition with AI allies, and competition with AI allies vs. all others as the visually most distinct comparison) were all non-significant (p > .05). The difference between AI and no AI conditions (conditions 1-3 vs. condition 4) was confirmed with custom contrast test (t(139.17) = 3.313, p = .001, d = 0.56). Additionally, an interaction effect between condition and previous experience was found (F(3, 116.26) = 3.704, p = .014), showing that the differences between conditions diminished the more experienced the participant was.

For tonic or phasic EDA, practically no synchrony-related results were found. Associations between EDA synchrony indices (tonic coherence, tonic cross-correlation, phasic cross-correlation) and conditions were all non-significant (p > .05).

The associations between self-reports and physiological synchrony indices were also analysed with a separate LMM (Table 6). Notably, tonic or phasic EDA synchrony indices were not significantly associated with self-reported social presence (all $p > .1$) or emotional empathy ($p > .5$).

Table 6. *Associations between physiological synchrony measures and self-reports.*

	Estimate	*SE*	*F*	*df*	*p*
Perceived Comprehension					
HF cross-correlation	0.091	0.031	8.589	1, 114.00	.004
SPGQ Empathy					
RMSSD cross-correlation[a]	-0.065	0.023	8.076	1, 136.72	.005
SPGQ Behavioral Involvement					
IBI coherence	-0.016	0.005	9.025	1, 139.69	.003
HF cross-correlation	-0.068	0.003	5.119	1, 132.12	.025
RMSSD cross-correlation[a]	0.033	0.016	4.391	1, 118.87	.038
SPGQ Negative Feelings					
IBI coherence[a]	-0.006	0.003	5.611	1, 115.73	.020
BEES					
IBI cross-correlation	0.026	0.009	8.641	1, 64.05	.005

Only significant associations are reported.
[a] Reported result is calculated with difference of participants, not mean.
Reproduced with permission of the copyright holder (Järvelä et al., 2013)

6.5 STUDY III DISCUSSION

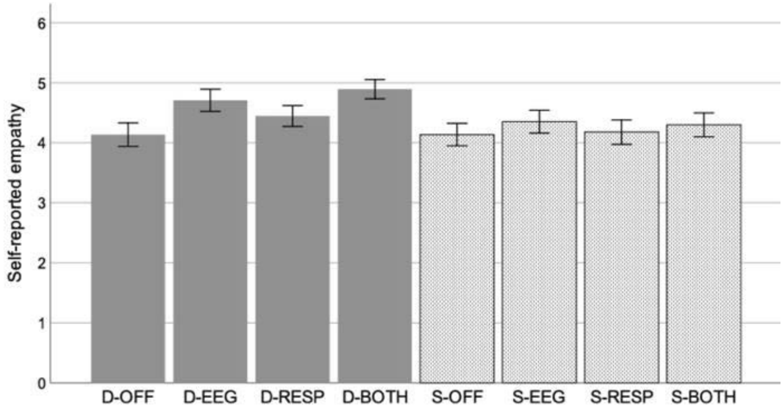
The central finding of Study III was that physiological synchrony was present in all conditions for both HR and EDA. The highest synchrony for HR measures occurred in the competitive condition where the computer AI was not present – indeed, in the contrast tests, this was the only comparison that showed a significant difference in HR synchrony between the tested conditions. No differences between competition modes were found, unlike in a similar study by Chanel et al. (2012). This finding leads to the interpretation that it was not the manipulation of competition or collaboration that affected the amount of synchrony within dyads, but rather whether there was a third actor – a computer – affecting the gameplay. The presence of an AI agent can be seen as a disturbance that weakens the interactivity within dyads as they are not the only relevant actors in the situation and the attention is divided. It is also possible that competition without any AI presence is stronger and purer form of competition with increased ego involvement in the outcome thus intensifying the social interactivity and physiological synchrony. This result supports the idea outlined in Study I that synchrony is not associated with negativity or positivity of the experience, instead being associated with the intensity of the social connection. Naturally, based on a single rather lightweight and fun computer game, caution is necessary before drawing interferences regarding whether competition vs. collaboration has effects on physiological synchrony in a broader sense or in a more serious high-stakes context.

Also, an interaction effect with game experience was found and the effect of AI presence was smaller when the players were more experienced. One possible interpretation for this result is that it reflects the skilfulness in focusing on game-relevant cues that more experienced players develop and their relative immunity to distractions. This interpretation implies that with more experienced players it is more about the game and less about the social consequences and dynamics of the playing situation.

The association between HR synchrony and self-reports suggests that physiological synchrony and empathy are connected, as correlations were found in both state and trait empathy self-reports. Behavioral Involvement was negatively correlated with HF cardiac synchrony measure and IBI coherence, and positively with RMSSD differences. In Study III, we interpreted these results to imply that when the social consequences of gameplay actions increase the attention of the player is more divided between the game and their pair which decreases the HF scores often associated with attention processes. However, the most consequential actions in this type of turn-based artillery game are highly asynchronous and often even to some degree unpredictable, and thus, the physiological synchrony related to social processes is higher when rated mean Behavioral Involvement is low. No associations between EDA synchrony and self-reports were found.

6.6 STUDY IV RESULTS

Self-reported empathy was higher in dyadic conditions than in solo conditions, except for the no biofeedback dyadic condition which was similar to solo conditions (Graphic 2). In dyadic settings, empathy was strongest with both adaptations on, highlighting how adaptations signalling the other person's emotional state support empathic processes in shared VR.



Graphic 2 Self-reported empathy scores per condition in Study V. D = dyadic, S = solo, OFF = no feedback, EEG = EEG feedback, RESP = respiration feedback, BOTH = EEG and respiration feedback. Reproduced with permission of the copyright holder (Salminen et al., 2019). © 2019 IEEE.

The self-reported within-dyad mean empathy was significantly associated ($F(1, 216.95) = 26.51$, $p < .001$) with the number of seconds of EEG frontal asymmetry synchrony between partners, but it was not associated with the number of respiration out-breath synchronizations ($p = .20$). Contrast analyses in Table 7 show that both EEG and respiration biofeedback were effective in supporting empathy either by themselves or both together.

Table 7. *Contrast analyses in Study IV.*

Empathy	Estimate	*SE*	*df*	*t*	*p*
Dyad vs. Solo	1.10	.27	254.22	4.03	<.001
EEG vs. None	.80	.19	235.49	4.18	<.001
EEG vs. Resp	.38	.19	256.45	1.97	.50
Resp vs. None	.42	.19	253.26	2.16	.03
Both vs. None	.90	.19	248.28	4.70	<.001

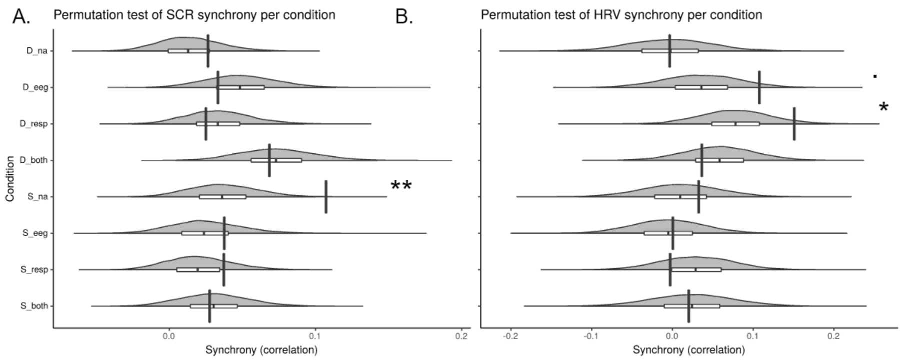
Resp = respiration, EEG = electroencephalography. Reproduced with permission of the copyright holder (Salminen et al., 2019). © 2019 IEEE.

6.7 STUDY IV DISCUSSION

Simply sharing the virtual environment with another person did not increase self-reported empathy compared with the solo mode, but the availability of biofeedback did. These results show that biofeedback is effective in supporting empathy in shared VR with limited interaction possibilities. Considering that EEG FA synchrony was related to within-dyad mean empathy but respiration was not, the results suggest that purposeful synchronization, which is possible for the participants with respiration but not EEG, is not particularly effective. The significant connection between EEG FA synchrony and empathy appears to be due the relation of frontal asymmetry to approach motivation and empathy.

6.8 STUDY V RESULTS

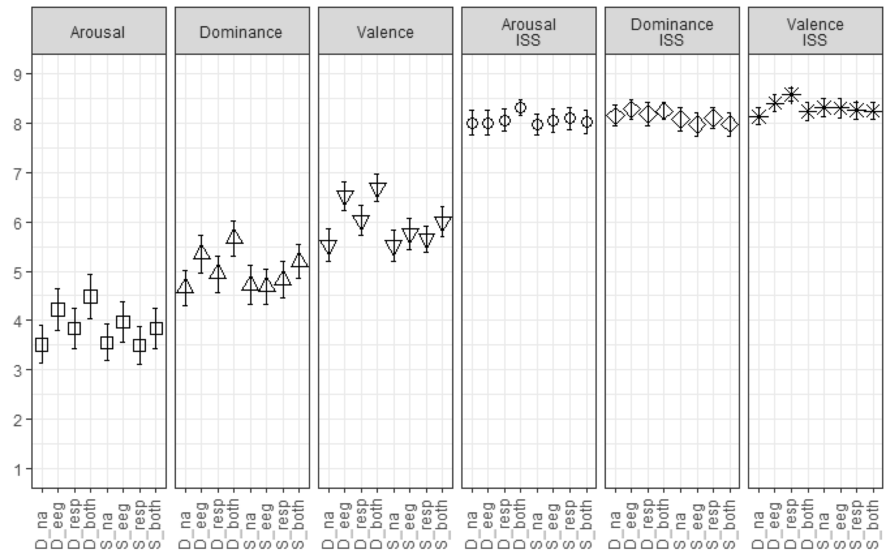
Permutation tests for EDA physiological synchrony (Graphic 3) revealed that within-dyad synchrony was not affected by solo vs. dyadic experimental manipulation or the different types of biofeedback ($p < .05$), except for the solo condition with no adaptation where significantly more EDA synchrony was observed than in the random sample ($p < .01$).



Graphic 3 Permutation tests for SCR (panel A) and HRV (panel B) synchrony per condition in Study V. Vertical lines represent the true dyad in relation to the distribution of 10000 randomly permuted pseudo-dyads.

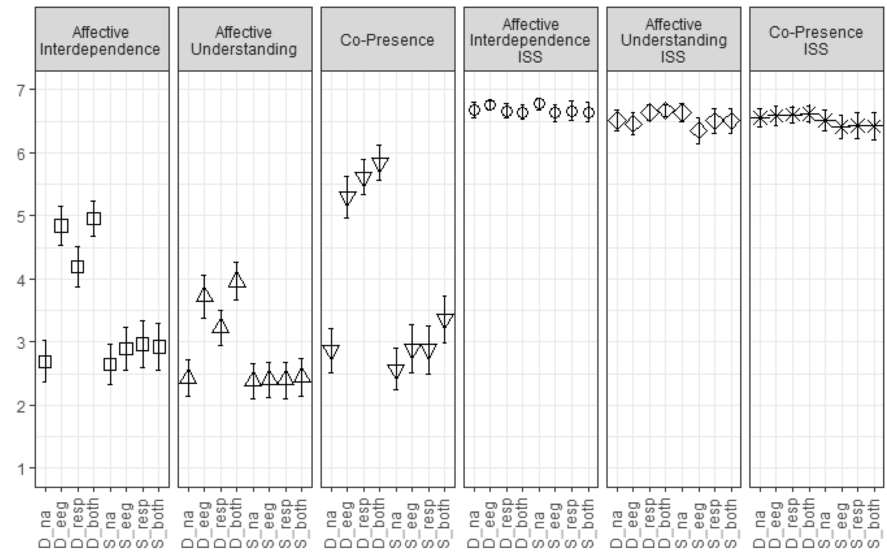
When conducting permutation tests for HRV synchrony (Graphic 3), similarly almost no significant differences compared with the random sample for solo vs. dyadic manipulation or different forms of biofeedback were found ($p > .05$). The only exception was the dyadic condition with respiration adaptation ($p < .05$).

Graphics 4-5 display the effects of dyadic EEG- and respiration-based biofeedback on emotions, social presence, and the associated intersubjective symmetries in a shared VRE compared with solo mode or no biofeedback. Intersubjective symmetries of bi-directional valence, dominance, and arousal ratings largely did not differ from condition to condition, except in the dyadic condition with respiration adaptation, where it was higher for valence, implying that shared VR with respiration adaptation was most efficient in supporting empathic accuracy.



Graphic 4 Self-reported Valence, Arousal, Dominance, and their intersubjective symmetries (ISS) in Study V.

When examining self-reported social presence ratings, all subscales were rated higher in dyadic conditions when either or both adaptations were on, and dyadic condition without adaptations did not differ from solo conditions. Intersubjective symmetries of bi-directional social presence subscales did not considerably vary from condition to condition, but the results imply that in general, assessing the partner's feeling of affective interdependence was easier than assessing affective understanding or co-presence.



Graphic 5 Social presence scores for Co-Presence, Affective Interdependence, Affective Understanding, and their intersubjective symmetries (ISS) in Study V.

In conditions where significant physiological synchrony existed, EDA synchrony was not related to any self-reported empathy, social presence, or emotional intersubjective symmetries, and HRV synchrony was not related to empathy but was correlated with Dominance ISS ($p < .05$) and Perceived Affective Interdependence ISS ($p < .01$).

6.9 STUDY V DISCUSSION

The EDA synchrony in the solo mode without any biofeedback can be interpreted as the ambient baseline effect of the VRE without any additional biofeedbacks or channels for interaction. I.e. the activity in the VRE itself causes the participant's arousal states to become similar in that environment. HRV synchrony in the dyadic condition with respiration feedback is plausibly a result of dyads synchronizing their breathing, leading to similar physiological states. Respiration-based biofeedback is arguably more explicit, concrete, simpler, and easier to comprehend than EEG-based adaptation, and related to a physiological signal that is far easier to manipulate.

Biofeedback as such provided support for social presence, and empathic accuracy (intersubjective symmetries), as shown in the self-reports. These processes were easier when sharing space with the partner, and having the extra information and interactivity provided by the adaptations available.

7 GENERAL DISCUSSION

This section summarizes the results of Studies I-V and focuses on how the empirical studies (II-V) answer the overarching research questions of this work and how they support the theoretical ideas presented in Study I. Limitations, relevance, applications, and future directions are also discussed.

7.1 RESULTS OVERVIEW

Overall, the results seem to support the idea that synchrony is associated with protosocial affective processes, however in these experiments it was not very sensitive to changes in social dynamics (e.g. competition vs. collaboration), whereas attention and limited social information played a significant role. Bearing in mind that the original studies had very different foci and experimental setups, the results are summarized and discussed in relation to the two overarching research questions. The aim is to better understand what inferences can be drawn from physiological synchrony indices in the context of digital media. First, we examine if and how physiological synchrony measures are sensitive to changes in social dynamics – mainly co-presence, interactivity, and collaboration – and then whether they are associated with self-reports related to protosocial affective processes and the early stages of social interaction, i.e. empathy and social presence.

RQ1 What social dynamics affect physiological synchrony?

Study I introduced the idea that physiological synchrony is related to the intensity of social connection regardless of whether it is positive or negative. This highlights the idea that synchrony itself should not be seen as automatically being desirable, even though previous studies had found a connection to positive outcomes such as increased empathy or team productivity.

In Study II, synchrony was the strongest when the dyads were non-co-located and had either chat option on a second screen or HR visualization to provide them with additional social information. Hypothetically, this can be explained by effects caused by first limiting the amount of social information through separating the participants into different physical spaces and then providing socially usable information through a single limited channel. Such a channel perhaps more easily grasps a person's attention, and hence, gives more weight to the social information acquired through it, amplifying the signal in a sense, whereas multiple channels compete for attention. This limitation of social information then could lead the participants to look for social cues more intensely, resulting in higher physiological synchrony.

A similar interpretation can be given to the findings of Study III, where physiological synchrony was the strongest when no AI agent was present and other conditions did not differ. This suggests that the presence of AI was a disturbance from the point of view of social interaction and physiological synchrony between participants. Without an AI agent, the participants could focus their attention more on each other and attribute all actions in the game to either themselves or their partner, thus creating a stronger social context without outside interference. The amount of synchrony was not responsive to changes in collaboration vs. competition modes, supporting the idea of Study I that the nature of the interaction is not necessarily linked to synchrony, but rather the intensity of the interaction. Though naturally in many digital games competitive play – player-vs-player (PVP) in particular – presumably is considerably more intensive than collaborative play, with the fun and lightweight game used in the experiment such a difference did not emerge.

In Study V, the amount of physiological synchrony differed only in two conditions: solo mode without any biofeedback and dyadic mode with respiration feedback. Notably, dyadic condition with both adaptations had less synchrony than with respiration feedback only. This supports the interpretation of findings of Studies II and III that a single information channel to focus on might be more effective in eliciting physiological synchrony than multiple channels. As discussed in the article, respiration feedback presumably was more intuitive both as a technical design in the VR and as a signal since respiration is considerably easier to control and to be aware of than EEG-based frontal asymmetry. This could also be the reason why respiration biofeedback was more efficient in eliciting physiological synchrony, and why EEG biofeedback was possibly interfering and dividing the attention of participants between a single intuitively interpretable source of information and another more confusing one, thus weakening the effect of respiration biofeedback alone. The fact that significant physiological synchrony also existed during solo meditation without any biofeedback, and consequently, no interaction between the participants, is interpreted to signal the basic environmental effects of using the VR environment itself and the meditation. This result highlights how physiological synchrony will occur without social interaction or co-presence if the simultaneous activity itself directs the two persons into similar physiological states. Indeed, separating that type of physiological synchrony from the synchrony that occurs due to social processes is highly important in experimental settings and when interpreting the results.

In summary, the studies suggest that limited other social information emphasizes the impact of biofeedback, and a strong focus on the partner seems to increase physiological synchrony, whereas any disturbances weakens it.

RQ2 Is synchrony associated with self-reported empathy and social presence?

The second overarching research question focuses on the association of physiological synchrony with self-reported empathy and social presence. This thematic question is drawn directly from Study I, where it was hypothesized that physiological synchrony would be connected to social presence and various aspects of social interaction.

Study II examined this connection and found HR synchrony to be associated with all measured social presence subscales, i.e. when higher HR synchrony existed, there was also a higher self-reported social presence on all scales. This result supports the idea presented in Study I that physiological synchrony could at least to some degree act as a measure of social presence. However, considering that particularly the chat option elicited social presence, and synchrony occurred the most when in different rooms with chat display on, we must consider the possibility that the attention-guiding properties of limited communication channels discussed in relation to RQ1 are causing both results; thus, the higher social presence and higher physiological synchrony may be merely co-occurring in this particular experimental setup and should not necessarily be interpreted too strongly to imply their direct relation. A possible interpretation is that increased interactivity with the chat option increased social presence which was then reflected in physiological synchrony. Based on this experiment alone, it is perhaps impossible to draw conclusions, but at the very least the results encourage further studies into the dynamics outlined in Study I.

As in Study II, HR synchrony was associated with the self-reported social presence in Study III, while no associations between EDA and self-reports were found. Perceived Comprehension, the difference in empathy scores, and the difference in Negative Feelings were associated with some of the cardiac synchrony measures. The synchrony increases when the participants feel they can understand each other or rate similarly in empathy or their emotional state, implying that a connection between empathy processes and physiological synchrony exists. Notably, also trait empathy scores were associated with increased cardiac physiological synchrony, suggesting that not only situational factors are involved but that more empathic persons tend to synchronize more easily. Results regarding the negative correlation of HF cardiac synchrony and Behavioral Involvement self-report suggest that the relation of synchrony measures and self-reports are highly context- and stimulus-dependant; an asynchronous gaming task with consequential but unpredictable results can lower attention-related synchrony, while Behavioral Involvement is still rated as high. Though, in retrospect, considering the rather modest effect sizes, caution in interpreting the results and assigning post-hoc explanations to the positive results is advisable.

In Study IV, the relation between self-reported empathy and EEG frontal asymmetry and respiration synchrony scores calculated online by the VR system was examined, and empathy was found to correlate with the number of seconds of both FA synchrony and respiration synchrony. In Study V, the same self-reported empathy was analysed in relation to the HR-based and EDA-based synchrony indices not used by the environment in the biofeedback, but no significant correlation emerged. Considering that the environment and the different biofeedback types in it were not strongly affecting physiological synchrony in HR-based or EDA-based indices in general, it is hardly surprising that they were not correlated with self-reported empathy either, while the self-report as such was sensitive to the different conditions and types of biofeedback. Similarly, various social presence subscales were not associated with physiological synchrony in Study V, except for intersubjective symmetry of Affective Interdependence, implying that mutual assessment of the degree that the pair is emotionally dependent on each other's actions is easier when in synchrony physiologically.

Displaying biofeedback did increase both empathy and social presence, as reported in Studies IV and V. This effect required a dyadic condition where the VRE was shared by the participants; mere solo biofeedback did not improve empathy or social presence. It is tempting to deduce that it was the part of the biofeedback that signalled that the dyad was synchronized that affected empathy and social presence, but as there was not a strict experimental procedure to separate the effects of sharing the VRE and the effects of biofeedback with or without synchrony information, it is impossible to say to what degree displaying synchrony biofeedback was effective in supporting empathy and social presence. In general, the results of Studies IV and V support the idea presented earlier; in technologically mediated communication where social information is scarce, biofeedback will provide usable information that supports empathy and social presence. Curiously, Study IV showcased how empathy was correlated with the signals used in the biofeedback, whereas in Study V no similar connection was found to other physiological signals. This is quite natural considering that in particular empathy-related EEG frontal asymmetry was chosen for the biofeedback, and that respiration is easiest to synchronize with the partner, especially compared with HR or EDA -based signals, which are mostly arousal and attention-related. In such an environment as used in Studies IV and V, they are most likely very similar from condition to condition and largely related to the baseline effect of the environment. Granted, the synchrony indices in Studies IV and V were calculated very differently, making direct comparisons slightly more uncertain.

In summary, with some limitations, physiological synchrony is connected to self-reported social presence and empathy, and both measures appear to be sensitive to similar changes in the experimental setup related to the amount of social information, interaction possibilities, and attention.

7.2 THEORETICAL CONTRIBUTIONS

To summarize, Studies II-V introduce a collection of results implying that physiological synchrony as a measure is sensitive to changes in empathy and social presence. These results provide experimental support for the ideas presented in Study I, i.e. synchrony measures are potential tools for examining social interaction in digital media. By extension, the idea presented in this thesis that it is the shared protosocial basis of social presence and empathy – possibly the social alignment system suggested by Shamay-Tsoory et al. (2019) – that is connected to physiological synchrony is also supported. In essence, the social alignment system based on herding behaviour aligns emotiovational and behavioural states of people, reflected in the alignment of ANS physiological signals, i.e. physiological synchrony. Empathy and social presence would be then in a sense the core manifestations of this social alignment and shown as an association between synchrony and self-report measures. This claim naturally requires considerably more experimental and theoretical work, including an extensive literature review of existing studies, an evaluation of whether they support this interpretation, and functional brain imaging studies, to become scientifically established.

Based on the few studies herein, the connection between physiological synchrony and protosocial affective processes seems to apply only to various ECG-based indices, not to EDA. While some cardiac measures are related to arousal similarly as EDA, changes in EDA signal are quite slow by nature, which may explain why certain tonic synchrony measures calculated from it are not very reactive. Phasic SRCs would possibly require a task or stimulus that is quite activating in order to be useful.

Considering Studies IV and V, we can see that changes in social presence or empathy between conditions that are apparent in self-reports are not automatically reflected in changes in physiological synchrony. A number of reasons could explain these results: Self-report biases highlighting the differences between conditions, or perhaps a minimum threshold level of social interactivity is necessary and minimalistic shared VR is not sufficient, or simply, that the experiment with its multi-dimensional bioadaptations was too complex to induce physiological synchrony.

All studies seemed to imply that the role of attention in modulating synchrony processes is an important one. Single social information channels to focus on seemed to increase physiological synchrony and social presence, while all distractions that divided attention – whether it was different forms of biofeedback, AI agents, or multichannel social interactivity – seemed to decrease them. This is in line with the EASI model's (Van Kleef, 2009, 2010; Van Kleef et al., 2010) prediction that the importance of emotions as social information is emphasized in situations where social information is scarce. This post-hoc summary observation regarding the role of attention is something that should clearly be studied further with well-controlled experiments with a specific focus on attention processes.

The results obtained from the studies do not strongly support either the contagion-based or the appraisal-based synchrony process (see Section 3.1) over the other. The summary finding regarding attention does not differentiate between the processes, as attention is plausibly central to both processes and distractions can disrupt either one. However, the finding that synchrony measures were not very reactive to changes in social dynamics (e.g. competition vs. collaboration) implies that the contagion-based process was more central, as the appraisal-based process should in theory be sensitive to such dynamics, but the collected data did not support this. Similarly, complexity of the stimuli was offered as one potential reason why the different biofeedbacks in Studies IV and V did not affect physiological synchrony, but cognitive appraisal processes should be able to differentiate between these and the difference seen in the synchrony measures. Naturally, strong inferences should not be drawn based on null results, and the experiments did not originally aim at separating these two processes, but tentatively the results suggest that the contagion-based process is more tightly associated with protosocial dynamics of empathy and social presence. This is in line with the idea that a herding behaviour-based social alignment system is central to physiological synchrony.

In conclusion, dyadic psychophysiology requires considerably greater collective efforts to become a reliable and valid method for assessing social interaction. Considering the many-to-many nature of psychophysiology in general, it is unsurprising that similar caveats apply to synchrony measures as well – topped with the additional complexity of dyadic social dynamics.

7.3 LIMITATIONS

The studies included in this thesis took place over many years in different research projects with varying research focuses. Considering the complexity of digital media, dyadic psychophysiology, and social interaction, it is rather difficult to draw strong conclusions based on these few studies, although they do all point in the same general direction. Physiological synchrony is itself such a complex topic that focusing purely on it would be warranted, instead of trying to use it as a method in studying something else and then assessing its reliability and validity. Over the years, the methodology related to physiological synchrony has developed considerably, but as a field, we are still far from having solid guidelines on how to calculate the indices from different signals, or from knowing which theoretical constructs are related to different indices. This work aims to contribute to the latter but is completely at the mercy of the former – in all studies the synchrony indices are calculated and analysed differently.

The studies herein were all conducted with modest sample sizes, and also considering the global reach of digital media, the sample was from a narrow demographic with little cultural or ethnic variety, which limits how boldly wider generalizations can be drawn. In retrospect, had project-driven research work allowed it, a series of more tightly focused, strictly controlled studies would have been better suited to investigate physiological synchrony in digital media and how it is related to social presence and empathy. Now, with a small number of broad experiments, the work is to a certain degree exploratory in nature. Specifically, the experiments conducted do not allow delving into the different sources of synchrony very deeply; the tasks used were asynchronous and that source of synchrony was controlled quite adequately, but going beyond that to examine e.g. the differences of the two routes to synchrony properly was ultimately impossible with the experiments presented here. Presumably, more focused experiments would have also brought out clearer effects and larger effect sizes – now the effects found are mostly modest in size.

It is impossible to say to what degree these differences affect the results and their validity; perhaps with more solid methodology, a clearer picture could be painted from the results and stronger contributions made. Certainly, the different studies would be more easily comparable if a more uniform methodology had been followed in all of them. Yet, in complex experimental settings and data, the methods – statistical methods in particular – always need to be fitted to the data at hand, and a long series of informed decisions have to be made at all steps in the process.

7.4 FUTURE DIRECTIONS

The limitations outlined above are essentially also a list of action points for future research. The field needs a long series of strictly controlled concise studies that aim at finding the theoretical constructs and (social)psychological phenomena associated with physiological synchrony. To advance the methodology itself, studies that systematically compare different methods of calculating synchrony indices and analysing them are required. Only then can more informed choices be made by the researchers in this field. Undoubtedly, the possibilities for this type of purely basic research-oriented systematic approach to physiological synchrony are limited, and in practice, the methodology will be developed at the same time as it is applied to studying various social dynamics in dyadic task situations, including multiple forms of digital media and technologically mediated communication. Hence, for the foreseeable future, it will continue to be challenging to draw inferences using this methodology, and its development will be distributed across multiple studies and research groups. On my part, I hope that this work contributes to the collective effort by outlining plausible theoretical constructs that could be assessed with physiological synchrony and also acts as a caveat to overly optimistic researchers regarding how this can be done in practice.

7.5 RELEVANCE AND APPLICATIONS

More generally, the broad-scale rise of dyadic neuroscience is a rather recent development, and its application to studying social phenomena, interaction, and dynamics, and the associated brain processes is just beginning. Roles, power differences, prejudice, ingroup/outgroup dynamics, etc. can all be potentially investigated using these methods in addition to social presence and empathy discussed in this work. This development could also mean that social neurosciences would become increasingly relevant in fields traditionally considered softer and that have tackled complex issues on higher levels of scientific explanations, and in a sense, enforce multi-disciplinary approaches to multiple fields.

Beyond strict scientific research, the application areas for these methods are vast. Therapy and patient-therapist -interaction was one of the defining contexts in the history of physiological synchrony (Kleinbub, 2017), and presumably, it will remain a central area in which these methods are studied and used. Affective computing and physiological computing are other areas where dyadic synchrony measures can find multiple uses and innovative pragmatic use cases as more and more wearables and other consumer-grade devices for gathering biosignals are gaining in popularity. The rapid development of VR technology combined with the environmental crisis is driving companies to develop and adapt communication technologies such as shared collaborative VR spaces as a concrete way of reducing business-related travel. These virtual environments are a major area in which synchrony measures can be applied to augment mediated social interaction, and I hope that this work contributes to that development in some small way.

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