Cognitive, Neural, and Social Mechanisms of Rhythmic Interpersonal Coordination

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Dedication

I dedicate this thesis to my husband Graham, my sister Annemarie, my children Erin,
Brandon, Sarah, Lexie, and Connor, my niece Aurora,
and my grandchildren Evelyn, Oliver, Alamein, and Kelani.
You are all the light of my life.

I also dedicate this thesis to the loving memory of my parents
Mark and Cathie Medaris,
I hope I have made you proud.

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Statement of Authentication

The work presented in this thesis is, to the best of my knowledge and belief, original except as acknowledged in the text. I hereby declare that I have not submitted this material, either in full or in part, for a degree at this or any other institution.

……………[redacted]………………..

Peta F. Mills

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List of Abbreviations

$\boldsymbol{\alpha}$	Phase correction parameter denoting the proportion of the previous asynchrony corrected
$\boldsymbol{\alpha_c}$	Phase correction parameter implemented by the virtual partner algorithm
$\boldsymbol{\beta}$	Period correction parameter
$\boldsymbol{\delta}$	Temporal anticipation parameter
$\boldsymbol{\gamma}$	Anticipatory error correction parameter
ADAM	Adaptation and Anticipation Model
ANOVA	Analysis of Variance
ATCI	Attitude Toward Computers Inventory
CMS	Common Mode Sense
EEG	Electroencephalography
IOI	Inter-Onset Interval
ITI	Inter-Tap Interval
LPR	Log Power Ratio
TMS	Transcranial Magnetic Stimulation
VP	Virtual Drumming Partner

Thesis Abstract

Humans possess the exceptional capacity to temporally coordinate their movements with one another with a high degree of accuracy, precision, and flexibility. Musical ensemble performance is a refined example of this, where a range of cognitive and sensory-motor processes work together to support rhythmic interpersonal coordination. However, the influence of social factors on the underlying cognitive-motor and neural mechanisms that facilitate rhythmic interpersonal coordination is yet to be established. This thesis draws on theoretical perspectives related to joint action, including co-representation, self-other integration and segregation, and theoretical models of sensorimotor synchronisation to consider this topic. Three experiments were conducted to investigate how social factors influence rhythmic interpersonal coordination. This broad empirical question was broken down by considering both extrinsic factors—such as the social context and perceived characteristics of an interaction partner (e.g. the degree of partner intentionality and responsiveness)—as well as intrinsic social factors, such as individual differences in attitudes and social preferences.

Extrinsic social factors were manipulated by using both implicit and explicit cues to communicate the intentionality of a synchronisation partner. Throughout all experiments, a computer-controlled adaptive virtual drumming partner (VP) was employed. The VP consisted of tempo-changing auditory pacing sequences and was programmed to respond to the participant's drum-stroke timing with various degrees of temporal error correction, simulating a more or less responsive drumming partner. In all experiments, the varying degree of adaptivity acted as the implicit cue relating to the intentionality of the drumming partner. In contrast, the explicit cue was manipulated in two different ways. In experiments 1 and 3, the

explicit cue was the presence of a co-actor and a verbal instruction to synchronise with either the co-actor or a computer-generated sequence of sounds. Whereas experiment 2 employed a humanoid robot with two different versions of 'social software' to better understand the importance of explicit signals intended to encourage social engagement. Here one version of software used explicit communicative cues such as speech, eye gaze, and body movements, and the other did not. To assess the effects of these extrinsic and intrinsic social factors, rhythmic coordination was examined in relation to processes at three levels of measurement—behavioural performance (experiments 1-3), underlying cognitive-motor mechanisms (experiments 1-3), and sensorimotor neural activity indexed by EEG alpha oscillations over central-parietal brain regions (experiment 3). The ADaptation and Anticipation Model (ADAM) of sensorimotor synchronisation was used to generate estimates of three cognitive-motor mechanisms, including the degree of adaptivity (reactive error correction), temporal anticipation, and anticipatory error correction. These parameters provided estimates of participants' representations of 'self', 'other', and the relationship between 'self' and 'other'.

As hypothesised, throughout all experiments, the results showed that for the implicit cue of partner intentionality, performance improved as the VP became more adaptive, with associated modulations in the underlying cognitive-motor mechanisms of synchronisation. This consistent finding demonstrates that people continuously monitor their partner's level of responsiveness and respond accordingly with alterations to their own basic interpersonal coordination mechanisms. In contrast, the results related to the explicit cue of partner intentionality were mixed across the three experiments. Firstly, at the level of the brain, the instruction that the synchronisation partner was a human led to modulations in sensorimotor alpha activity, suggesting that people are more likely to integrate their self-other representations with an unintentional partner. At the level of performance and associated cognitive-motor mechanisms, the explicit cues related to partner intentionality had effects that were modulated by individual differences in partner preferences. This finding suggests that top-down processes such as contextual beliefs can influence coordination performance and the degree to which the cognitive-motor mechanisms that facilitate synchronisation are employed. However, such effects may be subject to an individual's biases and social preferences.

This thesis concludes that extrinsic and intrinsic social factors affect rhythmic interpersonal coordination at multiple levels. A key aspect of this influence relates to how people regulate the integration and segregation of their representations of self and others. However, importantly, these effects are mediated by individual differences in intrinsic social factors such as personal preferences and biases. Top-down processes related to beliefs thus influence bottom-up sensorimotor processes during joint action, but the nature of this influence appears to be different for different people. This outcome highlights the necessity of taking individual differences into account, particularly when investigating the nuances of social processing during dynamic social interactions. Furthermore, the current findings suggest that beliefs about a partner during social interaction may be just as, or even more so, influential on performance than the actual characteristics of the partner. Recognising the potency of social beliefs has implications not only for research into basic psychological mechanisms underpinning rhythmic interpersonal coordination, but also for understanding the broader social dynamics of real-life situations involving cooperative joint action.

Note: Chapters 2 and 3 are journal manuscripts that have been submitted for publication. Details of each submission can be found on the title page of each of the relevant chapters. As the thesis contains journal manuscripts, there is some inevitable repetition across chapters. A brief preface is included before each of these chapters.

Chapter 1: Introduction and Literature Review

Humans have the extraordinary ability to coordinate their movements with others within space and time with extreme accuracy, precision, and flexibility. This ability enables cooperation between multiple actors, allowing people to complete a vast number of tasks that would not be possible by a single individual. Musical ensemble performance is just one example of the exceptional capacity of humans to coordinate. When members of an ensemble share an aesthetic goal, they can temporally coordinate their movements, each on their respective instruments, to generate a rich, dynamic, and cohesive musical soundscape that is beyond the possibilities of a solo performer. Although there is a multitude of evidence in many behavioural domains that attests to people's exceptional capacity to coordinate, there is still much to be learnt about the specific mechanisms that facilitate this ability, and importantly, how social factors may affect successful coordination. Being that rhythmic interpersonal coordination occurs (by definition) within a social context, there is a gap in the literature concerning how social factors influence both synchronisation performance and the underlying cognitive mechanisms that facilitate coordination.

As a social species, humans have evolved sophisticated mechanisms that facilitate interpersonal interaction (Brown & Brüne, 2012). Socially situated behaviour is pervasive, and social-cognitive processes are utilised within the vast majority of human activity. Previously, cognitive scientists have developed an in-depth understanding of many aspects of information processing within an individual. However, in recent years, there has been a growing interest in social behaviour and social information processing within psychology and cognitive neuroscience (Redcay & Schilbach, 2019; Schilbach et al., 2013). A key difference between studying individual behaviour as opposed to behaviour during social interaction is that during interpersonal interaction, the behaviour of each person is nested within the dynamics of the unfolding interaction. In other words, each party may continuously modulate their behaviour in response to actual, or inferred, characteristics and actions of their partner, which in turn may influence the partner's response, and so on as the interaction evolves.

As mentioned, rhythmic interpersonal coordination is a social activity; therefore, when studying the mechanisms that enable coordinated movement, it is of value to consider how context and social cognitive factors may affect interpersonal coordination performance. Social factors that may influence coordination can be extrinsic, such as the social context and perceived characteristics of an interaction partner (e.g. the degree of partner intentionality or a skill level), as well as intrinsic (e.g. social cognitive ability, attitudes, beliefs, or preferences). Understanding the influence of both extrinsic and intrinsic social factors on interpersonal rhythmic coordination will not only lead to a better understanding of general coordination processes but will also offer insight into social-cognitive processes in general. It also has relevance within the field of human-machine interaction, where the optimisation of how humans partner with robots and virtual agents to complete joint tasks is increasingly germane.

This chapter will review the literature relating to the behavioural and neural mechanisms that allow humans to coordinate movement. I will first discuss joint action research in a broad sense before discussing interpersonal coordination within the specific context of music with a particular focus on temporal and rhythmic domains. I will present a conceptual model that outlines the mechanisms that underpin rhythmic interpersonal coordination—namely, the ability to make accurate predictions about our own and others' forthcoming actions, and the capacity to respond and adapt to timing errors that previously occurred. I will then present research that speaks to the role that social factors may play, looking at both extrinsic and intrinsic factors. Specifically, the extrinsic social factors considered include the social context and perceived co-actor intentionality, the responsiveness of the co-actor, as well as social-communicative cues, while intrinsic social cognitive factors include individual differences in preferences and attitudes that may bias coordination performance with various types of partners.

1.1 JOINT ACTION

Research into joint action has investigated the cognitive, perceptual, and motor processes that allow two or more individuals to coordinate their movement in space and time (Vesper et al., 2011). This research has focused on both lower-level processing, such as perception-action coupling and spontaneous synchrony (e.g. Schmidt & Richardson, 2008), as well as higher-order processes such as shared intentions and 'theory of mind' —the ability to reflect on other people's mental states (e.g. Amodio & Frith, 2006; Atmaca et al., 2011; Humphreys & Bedford, 2011). Research into these topics has taken a broad view of joint action and has examined the mechanisms that support general joint action by considering a wide range of interpersonal behaviours, including swinging pendulums in synchrony (e.g. Schmidt & Richardson, 2008), rowing (Cuijpers et al., 2019), walking (van Ulzen et al., 2008), music-making (D'Ausilio et al., 2015), hand gestures (Dumas et al., 2010), and even the serving of champagne glasses (Pezzulo et al., 2017).

Theories of joint action suggest that several cognitive and neural mechanisms support interpersonal coordination. One of these is a close link between perceptual and motor processes in the brain (Kaplan & Iacoboni, 2006). Such theories posit that there is a common coding of perception and action (Prinz, 1997), such that perceiving an action in a co-actor will activate representations within one's own corresponding motor areas. Both behavioural and neurophysiological evidence has supported these theories. For example, behaviourally, it has been shown that perceiving an action of another can either facilitate or interfere with one's own concurrent action (Brass et al., 2001; Deschrijver et al., 2017; Roberts et al., 2016). While in neurophysiological research, the discovery of so-called ‘mirror neurons’ in macaques that respond both when the monkey acts but also when merely observing the actions of another monkey has provided physiological evidence that action execution and action perception share a common cognitive architecture (Rizzolatti et al., 1996; Rizzolatti & Craighero, 2004). Much research has been conducted into the presence and role of corresponding neurons with mirror properties in humans, and although this is still a much-debated topic, there is considerable support for an ‘action observation network’ (Cross et al., 2012) that appears to be functionally equivalent to a mirror neuron system.

The regions of the brain that are said to form this action observation network include areas traditionally involved in movement and action perception, including frontal, parietal and occipitotemporal regions, such as the premotor cortex, inferior frontal gyrus, the inferior parietal lobule and the medial temporal gyrus (Caspers et al., 2010; Cross et al., 2009). In support of this network, several studies have shown that similar brain regions are activated during both the performance of an action and observation of the action if the action belongs to the participant’s own motor repertoire (e.g. Calvo-Merino et al., 2005; Cross et al., 2006, 2009; Gazzola et al., 2006; Hadley et al., 2015; Orgs et al., 2008). Previous experience observing particular actions can also generate activation of the action observation network (Jola et al., 2012); however, activation is strongest when observing movements that one has physical experience performing. For example, Calvo-Merino et al. (2006) found increased activation of neural regions associated with the action observation network when expert dancers watched movements with which they had previous motor experience.

Another theorised function of the action observation network is the ability to form ‘co-representations’. Co-representation refers to the way humans mentally represent or ‘keep in mind’ a co- actor’s tasks and actions which thus enables interpersonal coordination during joint activities (Obhi & Sebanz, 2011; Sebanz et al., 2005). A popular empirical demonstration of co-representation within joint action research is the 'social Simon effect' (Sebanz et al., 2003). A traditional Simon task involves a person responding with either a left or right button to either a red or green stimulus that appears on either the left or right side of a monitor. Although the spatial location of the stimulus is irrelevant to the task, when the visual stimulus is positioned on the opposite side of the response button, there is an increase in reaction time, known as a spatial compatibility effect. However, this increase in reaction time does not occur when the participant is required to respond to just one of the stimuli in a Go/NoGo situation (for example, press the button when the stimulus is red).

Interestingly, however, when the Simon task is performed with a partner, where each participant is responsible for responding to only one type of stimulus (known as a social Simon task), the spatial compatibility effect is reinstated. This spatial compatibility effect occurs even though the individual's task is identical to the Go/NoGo version in the solo Simon task. It is argued that the re-emergence of the spatial compatibility effect in the joint action context rather than the solo Go/NoGo context provides evidence for the theory of co-representation during joint action (Sebanz et al., 2003). The argument is that during the joint condition, the representation of the partner's response leads to the increase in reaction time, reminiscent of when the participant performed both parts of the Simon task.

The joint spatial compatibility effect has been demonstrated behaviorally in many studies, across several different stimulus-response mapping tasks (e.g. Atmaca et al., 2011; Costantini & Ferri, 2013; Humphreys & Bedford, 2011; Schmitz et al., 2018; Sebanz et al., 2005; Sebanz et al., 2007; Stenzel et al., 2012; Tsai & Brass, 2007). Additionally, there is accumulating neurophysiological evidence for co-representation during joint tasks. For example, using electroencephalography (EEG), Sebanz, Knoblich et al. (2006) found more robust activation of the P3 response (a late positive event-related potential) during the joint condition of the social Simon task, compared to the solo condition. This effect may suggest the need to inhibit the action tendency that arises as a result of representing others' actions. Additionally, fMRI has revealed increased parietal and pre-central activity in the joint social Simon task than in the solo version (Wen & Hsieh, 2015). In sum, there is a plethora of both behavioural and neurophysiological evidence for the formation of co-representation of a co-actor's stimulus-response mapping during joint tasks (Sebanz et al., 2005; Sebanz, Knoblich, et al., 2006; but see Dolk et al., 2013 for an alternative view).

One functional role of co-representation is that it allows an individual to manage their own actions in a way that accounts for the contribution of the co-actor during a joint task. A crucial component of this function is the ability to accurately anticipate and thus predict the actions and movements of others (e.g. Colling et al., 2014; Manera et al., 2013). To coordinate action, it is crucial to predict not only what and where a co-actor's action will occur but when (Sebanz & Knoblich, 2009). Co-representation facilitates this ability within both temporal and spatial domains. Knowledge of our own motor system is used to generate predictions of others' actions through a process of mental simulation based on these co-representations (Knoblich & Sebanz, 2008; Welsh et al., 2020). This ability to predict future movements is a prerequisite of all inter-agent coordinated movement, and it is proposed that this ability requires a combination of bottom-up and top-down processes (Grigaityte & Iacoboni, 2016).

Bottom-up processing reflects the automatic processing of sensory information and is thus stimulus-driven, reflexive and relatively fast. Top-down processing, on the other hand, is effortful, flexible, and is driven by prior knowledge or contextual information. Top-down processes can modulate the bottom-up processing of sensory information, meaning that perception is a result of the dynamic interplay between both bottom-up and top-down processing (Brown & Brüne, 2012; Wilson & Knoblich, 2005). An example of top-down processes modulating bottom-up visual processing was demonstrated in recent years within the social-media debate about the colour of a dress. Even though the sensory information provided by the picture was the same, some perceived the dress as blue and black, while others perceived the dress as white and gold. Prior experience with light and shadow led to differences in the interpretation of the visual information resulting in differing perceptual experiences (Schlaffke et al., 2015). This example demonstrates that context and higher-order cognitive processes influence the way we not only attend to, but also interpret sensory information.

During social interaction, top-down processing may modulate bottom-up processes based on many factors, including (but not limited to) the information and beliefs one has about the co-actor, prior task experience or interaction experience with that co-actor, the situation or contextual demands, as well as an individual's underlying personality, attitudes, and biases (Grigaityte & Iacoboni, 2016). Top-down modulation of even basic perceptual processes has been demonstrated in the social-cognitive domain. For instance, von Zimmermann and Richardson (2016) found that eye movements differed based on the observer's beliefs about whether other people were present and what the other people were observing. Baess and Prinz (2015) also found that neural electrical activity related to early visual processing differed during a stimulus-response mapping task (a modified social Simon task) when performed alongside a co-actor compared to when performed alone. In addition to top-down processes modulating bottom-up processes within an individual, during social interaction, there is a dynamic interplay between bottom-up and top-down processing both within and between each interacting individual. Bottom-up information is modulated by the top-down processing of each social agent, which in turn may influence the subsequent actions of each individual, which can then lead to changes in the overall joint output (Grigaityte & Iacoboni, 2016). The ongoing dynamic nature of joint action highlights the necessity of adaptive and flexible perceptual and motor processes.

The mirror neuron system has been proposed as one of the neural foundations of bottom-up social processing (Grigaityte & Iacoboni, 2016) and may be the basis of action simulation (Gallese, 2005) and unconscious imitation (Iacoboni, 2009). The automatic mapping of others' movements onto our own motor system within the brain leads to a coupling between others' actions and our actions. It is argued that this coupling may lead to a blurring of the border between 'self' and 'other' and may lead to an integrated or merged self (Grigaityte & Iacoboni, 2016; Keller et al., 2016; Novembre et al., 2016). This integration of action processing between 'self' and 'other' enables basic social abilities such as action understanding and prediction and more complex social abilities such as empathy, perspective-taking, and inference of others' intentions (Kaplan & Iacoboni, 2006).

The sharing of neural apparatus to formulate a co-representation allows for integration between the self and other; however, an issue that arises with such integration is, how do we maintain separation between self and other? While an integrated co-representation facilitates coordinated movements, it is also necessary to know which actions are self-generated and which are produced by a co-actor (Schütz-Bosbach et al., 2006). Thus, it is not only our ability to integrate information from both self and other that is important, but also our ability to correctly segregate this information—to accurately assign authorship of actions. Therefore, during joint action, concurrent monitoring of the overall joint performance (integration), while also separately monitoring one's own actions, as well as the co-actor's actions (segregation), is needed (Novembre et al., 2016; Pacherie, 2014).

Both behavioural and neurophysiological evidence supports the concurrent segregation and integration of information during joint action. For example, Loehr et al. (2013) used EEG during a joint task to demonstrate that the sensory output of one's own and another's actions are integrated at early stages of auditory processing. In contrast, the two outputs become segregated at later processing stages, demonstrating that the brain differentiated between self-generated and other-generated sounds (at a millisecond timescale). Similarly, Novembre et al. (2016) identified particular patterns of neural oscillations within the alpha frequency band over central parietal regions, which differentially reflected the degree of self-other integration and segregation during joint action. These studies provide evidence that both integration and segregation of auditory information during a joint task are distinct processes that run in parallel to allow one to monitor the performance of self and other, as well as the joint action outcomes.

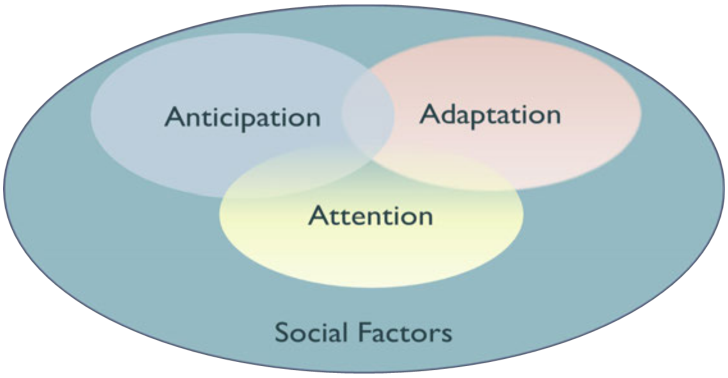
1.2 JOINT ACTION IN A MUSICAL CONTEXT

A highly refined form of joint action occurs when musicians coordinate while playing in ensembles. To achieve a coherent soundscape, musicians must coordinate the timing of their movements with a high degree of precision while also remaining responsive to a dynamic and often creative situation characterised by spontaneous expression. Much Western musical performance follows a rhythmic pattern that is based on an underlying metrical framework, where the relative intervals between sounds follow a particular pattern with an underlying regular pulse, the most salient of which is known as the beat. The beat provides a temporal reference point to aid multiple performers to coordinate their movement timing. However, not all instrumental parts necessarily play the same rhythm within a single musical piece, and a musician may modulate the underlying tempo or rhythm based on expressive intentions. Thus, during ensemble musical performance, rhythmic interpersonal timing requires ongoing reactive and proactive processing to monitor one’s own movement timing, the timing of other musicians, as well as the overall sound. Experienced musicians can successfully coordinate with each other, often at very fast time scales with extremely precise timing, while also remaining adaptive to the dynamics of musical performance (Keller, 2008, 2014). There is much research into the cognitive and psychological processes with which musicians achieve this balance between precision and flexibility during interpersonal coordination, leading to a theoretical framework that outlines these underlying processes, which will now be discussed.

1.2.1 A Theoretical framework of mechanisms that support musical joint action.

Keller (2008) proposed a conceptual framework of musical joint action that focuses on three core cognitive-motor skills that support interpersonal coordination during musical performance (see Figure 1). The first of these skills is divided attention, which allows a musician to attend not only to their own rhythmic timing, but also concurrently attend to the sounds and movements being produced by other performers, as well as the overall soundscape. The second skill, temporal anticipation, relies upon anticipatory mechanisms that allow a performer to predict the timing of others' movements in order to plan and coordinate their own movement. Finally, the third skill involves adaptive mechanisms that allow performers to respond to any timing variations (intended expressive timing deviations or unintentional errors) with adjustments to their own movement timing. It is theorised that these three skills combine to allow musicians to coordinate and synchronise their movement timing.

Figure 1.1 A Conceptual Framework of Musical Joint Action



Note: Attention, anticipation and adaptation are three core cognitive skills that interact to facilitate musical ensemble performance and are employed within a broader social context.

One key role of the combination of these three skills is to facilitate the integration and segregation of different streams of information at a millisecond timescale during musical performance. As mentioned in the previous section, the ability to form representations of a co-actor allows for precise simulation of their actions, facilitating accurate prediction of other's upcoming movements (and in a musical context, the timing of their next produced sound). Simultaneously, we monitor our own action timing relative to the sounds and actions of other musicians, and through a process of ongoing adaptation, we can flexibly respond to the dynamics of the unfolding musical performance. Additionally, to successfully coordinate, we need to integrate our predictions for the other actor with our own adaptive movement plans while also maintaining clear differentiation between the two. Thus, successful rhythmic interpersonal coordination requires an ongoing balance between self-other integration and segregation regulating the use of internal (knowledge) and external (environmental) sources of information (Keller et al., 2016; Novembre et al., 2016).

Finally, this theoretical framework of musical joint action also recognises that rhythmic inter-personal coordination occurs in a social context. Thus, social-psychological factors will interact with these core skills and may modulate the balance between self-other integration and segregation. Throughout the current program of research, I will use this framework as a basis for understanding how social-cognitive factors influence the underlying mechanisms that support interpersonal rhythmic timing. In particular, I will focus on two of the mechanisms—temporal anticipation and adaptive timing. I will also examine how these two mechanisms interact to regulate the balance between self-other integration and segregation during joint rhythmic activity and the role of attention in this regulatory process.

1.2.2 Divided attention.

Divided attention allows a musician to concurrently attend not only to their own rhythmic timing but also to the sounds and movements being produced by other performers, in addition to the overall soundscape (Keller, 1999). Attentional resources are prioritised, with own actions given higher priority over others' actions (Keller, 2001). This mechanism is cognitively demanding as it requires a musician to both segregate and integrate multiple streams of information (Uhlig et al., 2013). At different time points during performance, it is theorised that a musician can shift the amount of attentional resources that are allocated to each part. For example, a musician may pay more attention to another performer when coordinating entries in a musical piece. This ability enhances ensemble cohesion by allowing performers to adjust their performance based on online comparisons between their representation of the ideal sound and the actual sound (Keller, 2014).

1.2.3 Temporal anticipation

Anticipatory mechanisms allow an individual to accurately predict or anticipate other performers' upcoming movements and sounds. This predictive capacity enables individuals to begin their own movements early enough in time to achieve synchrony (Brown & Brüne, 2012). There are two routes along which anticipatory mechanisms may operate. The first is related to sensory expectations that are formed as a result of perceptual and motor resonance, which is triggered by the visual or auditory perception of another performer's actions. This route is believed to be an automatic, bottom-up process that evolves at short time scales (e.g. predicting the trajectory of an arm movement) (Keller et al., 2016; Phillips-Silver & Keller, 2012).

In comparison, the other pathway involves deliberate mental imagery and simulation of a co-performer's upcoming movements and sounds (Keller & Appel, 2010). It is proposed that such imagery is based on knowledge of the shared representations and goals of the ensemble (Keller, 2008, 2014). Anticipatory mechanisms rely on cognitive resources such as working memory, and individuals differ markedly in anticipatory ability (Pecenka & Keller, 2011). In musical contexts, musicians predict the timing of subsequent sounds based on regular rhythmic patterns within the music. However, anticipatory mechanisms also allow musicians to predict changes in the musical timing (e.g. tempo changes), such as those that occur during an expressively motivated musical performance (Pecenka & Keller, 2011; Rankin et al., 2009).

Individuals differ in anticipatory ability, with some being very good at predicting tempo changes while others follow or ‘track’ these changes (Michon, 1967; Rankin et al., 2009), which affects the quality of interpersonal synchronisation. For example, using a dyadic tapping task, Pecenka and Keller (2011) found that synchronisation performance was best when two high predicting individuals (those who anticipated tempo changes more than followed tempo changes) were paired together, compared to pairs of low predicting individuals (those that followed more so than predicted tempo changes), or mixed high and low dyads. Similarly, Keller and Appel (2010) found that individual differences in anticipatory auditory imagery predicted ensemble coordination.

1.2.4 Adaptive mechanisms (Error correction).

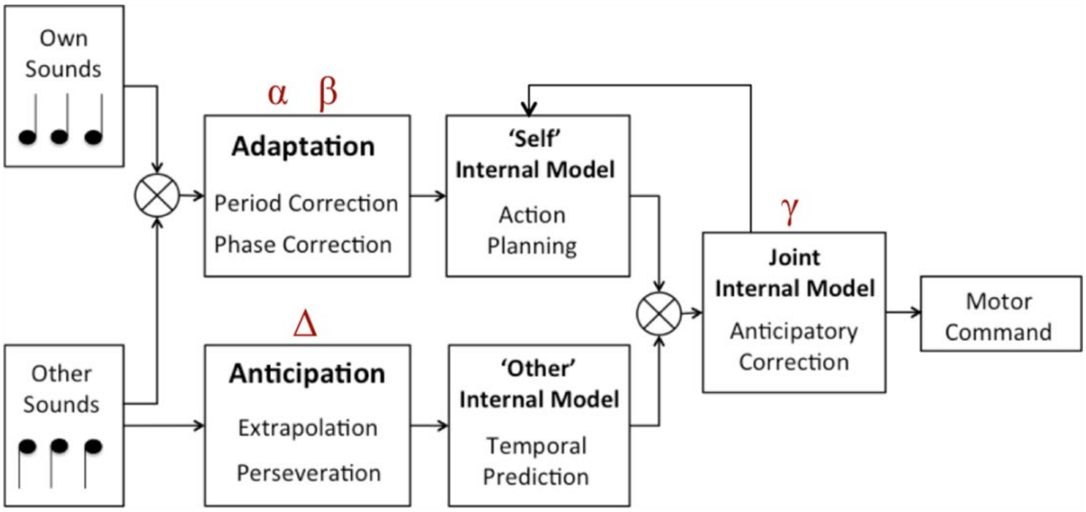
The third core ensemble skill, adaptive timing, allows musicians to continually monitor and respond to each other’s intentional and unintentional timing deviations. Adaptive timing is mutually employed by multiple musicians, each responding to asynchronies by adjustment of their subsequent actions (Goebl & Palmer, 2009). It is assumed that an internal timekeeper regulates each performer’s action timing by means of neural oscillations at a tempo that matches the associated beat (Wing & Kristofferson, 1973). With the addition of linear error correction mechanisms, this timekeeper allows synchronous movement to an external stimulus sequence (Vorberg & Schulze, 2002).

Linear error correction is a mechanism that underlies adaptive timing and has been studied extensively in sensorimotor synchronisation tapping studies (e.g. Repp, 2001, 2011; Repp & Keller, 2008; Vorberg & Schulze, 2002). There are two types of error correction, period and phase correction, each an independent process that functions to reduce asynchrony in timing (Mates, 1994; Vorberg & Schulze, 2002). Period correction is understood to be an intentional adjustment of the internal timekeeper and requires the conscious perception of a tempo change (Repp et al., 2012). Phase correction, on the other hand, is an automatic process that corrects deviations in timing continuously by adjusting the timing of each movement based on the previous asynchrony, while leaving the period of the internal timekeeper unchanged (Keller, 2008, 2013; Repp, 2001; Repp & Keller, 2004). This process occurs at a millisecond timescale even without conscious awareness of asynchrony. The key difference between the two types of error correction is that phase correction is automatic and does not change the timekeeper interval beyond the current movement cycle. In contrast, period correction is intentional and causes a change in the timekeeper interval that persists across subsequent cycles until period correction is again applied. In this way, period correction results in a change of tempo.

1.2.5 The ADaptation and Anticipation model (ADAM).

To understand the relationship and interaction between anticipatory and adaptive mechanisms, Mills, van der Steen, Schultz, and Keller (2015) assessed the relationship between anticipatory and adaptive (phase correction) mechanisms by measuring individual differences in these capacities. There was a significant positive correlation between the two measures, indicating that these two mechanisms are related. Those that predicted (anticipated) more also engaged in higher levels of phase correction (adaptation). To account for this finding, the Adaptation and Anticipation Model (ADAM) was developed (Harry & Keller, 2019; van der Steen & Keller, 2013; van der Steen, Jacoby, et al., 2015). This model accounts for both adaptive (phase and period correction) and anticipatory mechanisms within the one framework and also incorporates how these two capacities integrate to facilitate rhythmic coordination. A schematic of the ADAM model is presented in Figure 1.2.

Figure 1.2. Schematic Diagram of the Adaptation and Anticipation model (ADAM)



Note: The synchronization of one's own actions with another's actions is facilitated by temporal adaptation mechanisms that influence action planning, anticipation mechanisms that enable temporal prediction, and a joint mechanism that allows for anticipatory correction, which reduces discrepancies between plans and predictions. Within ADAM, adaptive mechanisms are represented by the parameters α (phase correction) and β (period correction), while anticipatory mechanisms are represented by Δ, whereas the joint internal model instantiating anticipatory error correction is represented by γ (Figure adapted from Harry & Keller, 2019).

ADAM consists of three modules that include parameters representing (1) adaptive processes, (2) anticipatory processes, and (3) a joint model that represents the integration and interaction between adaptive and anticipatory processes. The adaption module represents reactive error correction processes that occur when monitoring one's own timing compared to an external source. The anticipation module represents predictive processes that allow temporal estimation of the upcoming timing of the external source. The joint module instantiates the interaction between adaptive timing and temporal anticipation. This module compares the planned timing of one's next movement (generated by the adaption module) with the predicted timing of a synchronisation partner's movement (generated by the anticipation module). It then corrects for a proportion of any anticipated discrepancy. This process enables a form of anticipatory error correction by adjusting the timing of planned movements to correct for potential synchronisation errors, even before they occur (Harry & Keller, 2019; van der Steen & Keller, 2013).

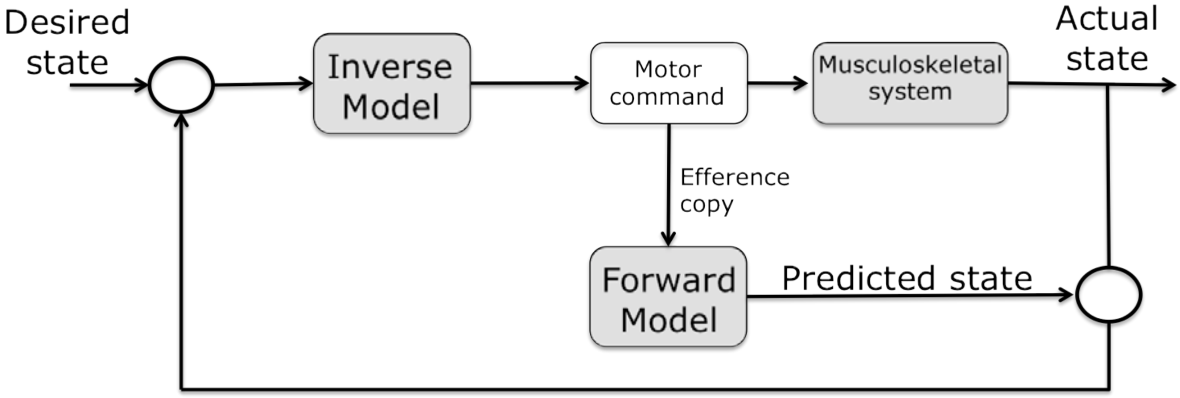
A crucial theoretical underpinning of ADAM is the concept of internal models, which provides a theoretical basis of the neurological foundation of our ability to simulate our own and others' actions. Notably, the theoretical understanding of the coupling between these internal models for 'self' and 'other' forms the foundation of the ability to integrate motor plans for self and other actors, which underpins the ability to synchronise behaviour. The following section will discuss these internal models in more detail.

1.2.6 Internal models.

As proposed by Wolpert, Miall, and Kawato (1998), internal models have been theorised as a primary mechanism that supports movement and temporal sequencing of actions through action simulation. Keller (2008) suggested that such internal models drive the mental imagery and simulation processes that allow a performer to anticipate co-performers actions in the musical joint action domain. These internal models allow mental simulation of a movement and the potential outcome of such a movement to be carried out prior to an action. For this to occur, the central nervous system needs to have had prior experience of the effect of efferent neural motor signals on the body and environment (Wolpert et al., 1998). This process helps with movement efficiency by allowing predicted sensory feedback to inform the accuracy of a movement before the arrival of actual sensory feedback (Aschersleben et al., 2002; Wolpert et al., 1998).

Two types of internal models have been distinguished (see Figure 1.3). Forward models represent causal relationships between motor commands and their effect on the environment and the sensory consequences on the body. For example, forward models explain why humans cannot tickle themselves. An internal model can precisely anticipate the sensory feedback that would result from a motor command to tickle one's own arm. This anticipation leads to a reduction or attenuation of the sensory response (Blakemore et al., 2000). An example of a forward model in the instance of someone striking a drum may be: ‘when a motor command occurs to move the arm holding the drumstick toward the drum pad with a specific amount of force, the predicted outcome will be the sound of a drumbeat at this approximate time’.

Figure 1.3 Schematic Diagram How Internal Models Facilitate Movement



Note: An inverse internal model initiates from the desired state (or sensory consequence) and simulates the actions needed to produce this state. In comparison, a forward model generates an efference copy of a motor command to predict what and when the outcome from that action will occur.

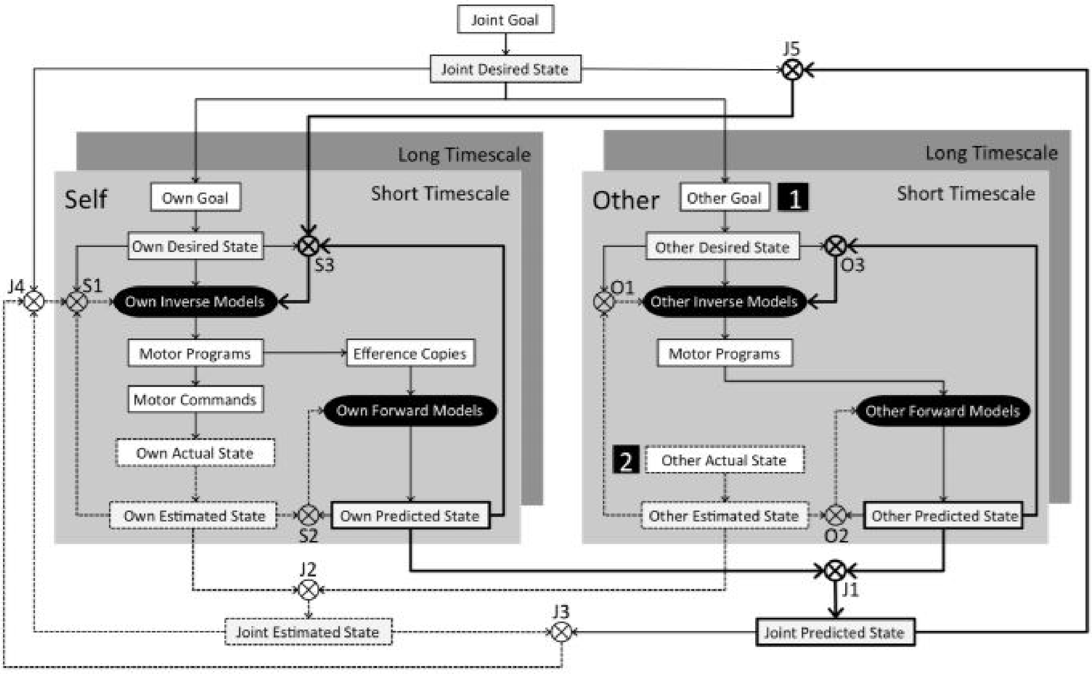
Inverse models are complementary to forward models in the sense that the directionality of the transformation process is reversed. These models begin with the desired outcome and calculate the necessary motor commands to produce the movements required to reach such an outcome. For example, ‘to produce a loud drum beat at this particular time, these motor commands are required to generate the necessary arm movement’.

Keller et al. (2007) investigated action simulation driven by internal models by asking pianists to play one part of a piano duet in synchrony with recordings of either themselves or others playing the complementary part. Pianists were better at synchronising with their own recordings than with others’ recordings, suggesting that synchronisation was enhanced when the internal simulation of the accompanying role was most accurate (i.e. when the pianists imagined actions of their duet partner were matched with the recording of their own actual movements). This finding provided initial support for the hypothesis that internal models facilitate action simulation, which enables anticipation and prediction of others' movements, which in turn leads to better synchronisation.

It has been hypothesised that forward and inverse models operate simultaneously for not just execution of one's own actions but also for anticipating and predicting the actions of others (Keller, 2008, 2013; Pacherie, 2008; Wolpert et al., 1998, 2003). Through observation of others' actions, forward models allow simulation and, thus, estimation of others' movement outcomes. On the other hand, inverse models enhance synchronisation by representing others' intentions and performance goals and using this knowledge to predict what actions will subsequently be produced (see Figure 1.4). According to the above sources, it is thus theorised that the ability to model the actions of others is an integral aspect of coordinated behaviour. In support of this, it has been found that deficits in the ability to model the behaviour of a co-actor (e.g. as occurs in autism) can impair performance in joint action tasks (Stoit et al., 2011).

Keller et al. (2016) hypothesised that the link between our ability to predict others' timing and how we reconcile that with one's own error correction processes might be due to a coupling between 'self' and 'other' internal models. The concurrent use of both forward and inverse models for self (error correction) and other (temporal anticipation) enables integration between one's own motor simulation with an interaction partner's predicted forthcoming actions or sounds. As previously mentioned, this coupling has been instantiated within the ADAM architecture as the 'joint internal model' (Harry & Keller, 2019; van der Steen & Keller, 2013) and regulates the balance between the output of both the adaptation and anticipation modules. This joint internal model thereby represents the degree of self-other integration and segregation at a sensory-motor level, and moreover, may allow for a form of

Figure 1.4: Schematic of the relationship between internal models for self and other



Note: Internal models for self and other interact to support interpersonal coordination in a musical context (figure is taken from Keller, Novembre, & Loehr, 2016).

'anticipatory error correction' whereby potential timing errors can be anticipated and then corrected before they occur (van der Steen & Keller, 2013).

Both temporal anticipation and adaptive timing have previously been studied extensively (however, generally separately) within the sensorimotor synchronisation tradition, where participants tap in time with a pacing sequence. Below, I briefly introduce this sensorimotor synchronisation paradigm and explain how it will be used throughout the current thesis to investigate rhythmic interpersonal coordination.

1.3 SENSORIMOTOR SYNCHRONISATION AND THE TAPPING PARADIGM.

Sensorimotor synchronisation is the temporal coordination of a movement with a predictable external rhythmic stimulus (Repp, 2005; Repp & Su, 2013). There has been much research into the basic mechanisms of sensorimotor synchronisation from both behavioural and neuroscientific perspectives (for reviews, see Repp, 2005; Repp & Su, 2013). Behavioural research has spanned a broad range of tasks from simple finger taps in time with a metronome (e.g. Repp et al., 2011) to musical ensemble performance (e.g. Keller & Appel, 2010). A popular and convenient method of studying a basic form of sensorimotor synchronisation is the tapping paradigm. Here, individuals are asked to tap a finger in time to a simple metronome or sequence of events. These sequences can be auditory, visual, or multimodal, however, people are most accurate with auditory sequences (Hove et al., 2013).

The auditory sequences may be varied depending on the focus of the research question; they may be isochronous (regular evenly spaced tones), tempo changing (speeding up and slowing down), or rhythmic (following a non-isochronous temporal pattern). The auditory sequences are characterised by the timing between each tone, known as the inter-onset interval (IOI). The taps from a sequence can be measured in terms of the time between each tap or the inter-tap interval (ITI). This simplified task allows for the controlled investigation of the mechanisms involved in interpersonal joint action at a millisecond timescale (Repp, 2005; Repp & Su, 2013).

Using the tapping method, synchronisation is generally assessed in terms of accuracy and precision (stability). Accuracy is evaluated by measuring synchronisation errors or asynchronies (defined as the temporal difference between the onset of a tone and a tap), while precision is assessed in terms of variability (how much timing fluctuates between successive taps). There are substantial individual differences in sensorimotor synchronisation ability, with variability across people in both accuracy and variability (Mills et al., 2015; Pecenka & Keller, 2011; Repp & Su, 2013).

Traditional SMS research conducted in the laboratory has used finger tapping tasks, however recently, several studies have instead used a drumming task where participants use a drumstick to strike a drum pad (Fujii & Oda, 2009; Manning et al., 2017; van der Steen, Schwartze et al., 2015). This method increases ecological validity while also allowing for more robust data collection with less missing data. Additionally, timing precision is improved with lower variability with stick tapping compared to finger tapping (Fujii & Oda, 2009; Manning et al., 2017). Despite these improvements, the results of studies using this drumming method are commensurate with results obtained from traditional finger-tapping tasks.

Rhythmic sensorimotor synchronisation tasks are a valuable tool to investigate the mechanisms underlying interpersonal because of the simplicity of the task and the millisecond timescale of the coordination dynamics. A useful variation of this tool, particularly when investigating rhythmic interpersonal coordination is the Virtual Partner (VP), which can simulate an adaptive interaction partner allowing investigation of how adaptiveness can affect synchronisation performance.

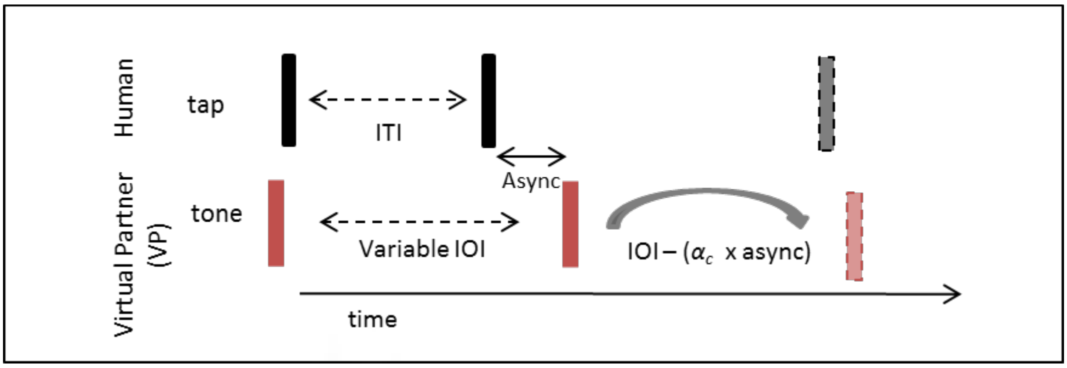
1.3.1 The virtual partner (adaptive metronome)

A limitation of much previous research that has used tapping studies to investigate adaptive timing is that participants have synchronised with computer-generated sequences that are unresponsive to the human behavioural response. This experimental design does not constitute an ecologically valid model of the cooperative and dynamic synchronisation of multiple musicians actively engaging in error correction concurrently and does not account for the complexity of the social context of synchronisation. To address this issue, Repp and Keller (2008) employed a 'virtual partner' (VP). This adaptive metronome was a step toward investigating interpersonal synchrony with the rigour and control of the sensorimotor synchronisation paradigm (Repp & Su, 2013). The VP works using a mathematical algorithm that enables the computer to engage in a controlled simulation of error correction and thus 'interact' with a participant.

When employing error correction during a VP synchronisation task, the computer is programmed to respond to an asynchronous tap by altering the timing of the subsequent tone.

For example, when implementing phase correction, if a participant were to tap slightly too early, the VP will respond by adjusting the timing of the following tone to sound earlier (see Figure 1.5). By changing the proportion of the asynchrony corrected for, the degree of error correction employed by the computer can be prescribed and manipulated by an experimenter. By varying the degree to which the computer adjusts the timing, it is possible to simulate a musical partner who is either more or less responsive (Fairhurst et al., 2013; Repp & Keller, 2008). Having flexibility related to the degree of error correction employed is analogous to real human partnering, where the skill level of musical partners is variable.

Figure 1.5: Overview of the adaptive timing mechanism of the virtual partner.



Note: The adaptive timing mechanism of the virtual partner incorporates phase correction in response to the participant’s drum-stoke timing. Phase correction alters the timing of the subsequent inter-onset interval (IOI) by adjusting for a proportion (α_c) of the previous asynchrony (async.) between the last pacing event (tone) and corresponding drum tap.

Previous studies employing the VP have found that coupling strength is optimal (defined as minimal variability of asynchronies) when both the virtual partner and the participant engage in moderate amounts of phase correction (0.3 – 0.6) (Fairhurst et al., 2013; Mills et al., 2015; Repp & Keller, 2008; van der Steen & Keller, 2013). In this instance, both the human participant and the virtual partner each moderately adjust their timing toward each other, minimising the asynchrony. In contrast, synchronisation is hindered when the computer is overly adaptive (i.e., it over-corrects the asynchrony). This hindrance is because phase correction in the human participant is automatic, leading to potential overcompensation, where the two miss each other by going too far in opposite directions.

The VP can also employ phase correction to differing orders where it uses asynchronies from different lags to adjust the timing. For instance, in second-order phase correction, the VP would assess the second to last asynchrony rather than the immediately preceding asynchrony. Second-order phase correction is theorised to be employed when task demands are high, for instance, when the sequence is difficult to synchronise with, such as fast tempi or complex rhythms (Pressing, 1999; Repp et al., 2012; Semjen et al., 2000).

1.3.2 Investigating temporal anticipation and adaptation within the sensorimotor synchronisation paradigm

Previous research has used the SMS paradigm to investigate both temporal anticipation and adaptive timing. Temporal anticipation has traditionally been studied using tempo changing sequences that are non-adaptive (e.g. Colley, Varlet et al., 2018; Mills et al., 2015; Pecenka & Keller, 2011), whereas research investigating adaptive timing has utilised the adaptive VP to understand error correction processes (e.g. Fairhurst et al. 2013, 2014; Mills et al., 2015; Repp & Keller, 2008). The current thesis will combine these techniques within the one task by using tempo changing sequences that concurrently implement the adaptive function of the VP, resulting in sequences that are tempo changing while also being responsive to the participant’s timing to various degrees. These tempo-changing adaptive sequences mimic real-life expressive musical interaction between two humans and are a novel use of the VP, enabling investigation of the effects of social beliefs on rhythmic interpersonal coordination.

1.4 THE INFLUENCE OF SOCIAL FACTORS ON RHYTHMIC INTERPERSONAL COORDINATION

Joint action research suggests that there are many social factors that may influence the way a person behaves in a joint task. The knowledge that a task is being conducted in an interpersonal context appears to alter the joint action mechanisms of co-representation and action simulation that are employed in order to coordinate during a joint task (see section 2). However, as previously mentioned, studies that have investigated anticipatory mechanisms and adaptive timing using sensorimotor synchronisation tasks have typically been conducted in an individual context. This design ignores the interpersonal nature of musical joint action and the possibility that social factors may modulate synchronisation performance. The virtual partner partly addresses this issue by allowing mutual adaptation in a simulated human interpersonal context. However, similarly, most studies that have used the virtual partner have predominately done so without any social context. Thus, although the auditory sequences were adaptive, the participants were aware that they were synchronising with a computer that does not have the social capacities of a human (e.g. co-representation and action simulation). In comparison, during synchronisation in an interpersonal context—where social cognitive capabilities may be attributed to a synchronisation partner—the operation of anticipatory and adaptive mechanisms examined using the VP may differ from synchronisation in a solo context.

In addition to the potential influence of social factors on rhythmic coordination, coordinated rhythmic movement can also have a bi-directional effect on social outcomes. For example, social benefits arise after synchronous movement with another, such as increased prosocial behaviour, interpersonal bonding, liking, and trust (e.g. Cirelli et al., 2014; Kokal et al., 2011; Marsh et al., 2009). For instance, Hove and Risen (2009) demonstrated that interpersonal synchronisation during a finger-tapping task led to increased liking and affiliation. However, the nature of the bi-directional links between social factors and rhythmic interpersonal coordination are poorly understood at both a behavioural and neurophysiological level (Keller et al., 2014), and further research is needed to understand this relationship better.

Therefore, it is essential to consider the role of social factors when investigating rhythmic interpersonal coordination during musical performance; and to do this at multiple levels of measurement. Firstly, the effect of social factors can be assessed at the level of behaviour by evaluating synchronisation performance. Secondly, it can be considered at the level of cognition by assessing the core cognitive-motor skills that facilitate coordination. Thirdly, this effect can be examined at the level of the brain by investigating the neural correlates of synchronisation within various interpersonal contexts. Understanding the effect of social factors on rhythmic interpersonal coordination at all three levels—behaviour, cognition, and brain activity—will provide insight into not only the mechanisms that support rhythmic interpersonal coordination but also social cognition in general. The current project contributes to this endeavour by investigating several potential social factors that may impact synchronisation performance and the underlying cognitive and neural mechanisms that support interpersonal rhythmic coordination.

There are numerous potential social factors that may impact interpersonal rhythmic coordination. These factors may be extrinsic to an individual, such as the social context or characteristics of the interaction partner. For instance, whether or not a co-actor is present, who or what the co-actor is, the skill and responsiveness of the co-actor, as well as whether the co-actor is an interactive and intentional agent (Fairhurst et al., 2013; Novembre et al., 2014; Tsai & Brass, 2007; Tsai et al., 2008). Alternatively, intrinsic social cognitive characteristics, such as attitudes, beliefs, and preferences, may equally impact interpersonal coordination performance (Kaplan & Iacoboni, 2006). Below, I elaborate on some of these extrinsic and intrinsic social factors and present evidence for their potential effect on rhythmic interpersonal coordination. I also consider the possible interaction between these extrinsic and intrinsic social characteristics.

1.4.1 Extrinsic social factors

1.4.1.1 Social context

The social context (i.e., the presence and interaction with another active agent) may influence how people engage in a rhythmic coordination task. The knowledge that the tapping partner is an agent who can actively and intentionally choose to coordinate, using similar coordination mechanisms, may change how one approaches a synchronisation task and thus alter synchronisation performance. Kirschner and Tomasello (2009) found that the variability of asynchronies decreased in children when drumming in a social situation with an adult as opposed to drumming with either a drumming machine (audio-visual condition) or a pre-recorded beat (audio-only condition). They argued that synchrony was facilitated during the social context because this elicited greater motivation to engage in synchronised movement by creating a shared representation of the joint action task.

As previously mentioned, much research into joint action has demonstrated that there are differences when performing a task with an interactive partner compared to performing the same task alone (e.g., the social Simon task—see section 2). This effect of social context has also been demonstrated with the mere belief of an interaction partner (Atmaca et al., 2011). For example, Tsai et al. (2008) conducted a joint action experiment where participants believed they were interacting with either an unseen human or a computer. In reality, the participants were interacting with the computer in both conditions. The results showed that participants' reaction times were modulated based on the portrayal of whether or not there was an interaction partner, demonstrating that merely being told that there is a co-actor is sufficient to elicit the joint action effect. This effect was also observed in the brain's electrical activity with changes in two event-related potentials—the P300 and stimulus-locked lateralised readiness potentials.

Changes in neural electrical activity depending on the joint context have also been demonstrated during rhythmic interpersonal coordination tasks, with modulations within the alpha frequency band (8 – 12 Hz) observed during joint finger-tapping tasks. Greater desynchronisation over sensorimotor areas within this frequency range (indicating an increase in activity) was found when participants synchronised finger taps with another person instead of tapping their fingers at their own pace (Naeem et al., 2012b). Likewise, Konvalinka et al. (2014) asked pairs of participants to synchronise finger taps and found greater suppression of oscillations in the low alpha range (~10hz) when synchronising with a human partner than with an isochronous sequence of sounds played by a computer. Similarly, Tognoli et al. (2007) also found greater alpha suppression in dyads making synchronised finger movements compared to unsynchronised movements. These findings provide evidence for co-representation at the level of the motor control system, and moreover, suggest that such representations are modulated by social context and the joint nature of an interaction task.

Further neurophysiological evidence for the effect of social context was also demonstrated by Novembre et al. (2012) in a musical joint action experiment. These authors used Transcranial Magnetic Stimulation (TMS) to investigate the effect of social context on the human motor control system. TMS is a non-invasive technique that stimulates a chosen brain region to temporarily modulate, disrupt or facilitate its activity. One common usage involves stimulating the right primary motor cortex with a single pulse to induce a muscle contraction in the left hand. The amplitude of this muscle contraction (known as a motor evoked potential) can be measured and is considered an indicator of motor resonance within the motor control system. Novembre et al. (2012) asked participants to play the right-hand part of a piano melody either by themselves or while the experimenter simulated the left-hand part being played by an accompanist. The two conditions were presented both with and without auditory feedback. Differences in motor evoked potentials were observed when a participant believed they were playing the piano piece with another person, as opposed to playing the piece in a solo situation, even without auditory feedback. These results provide further evidence that, at the level of the neural motor control system, people represent the actions of a co-actor during musical joint action.

1.4.1.2 Perceived co-actor intentionality and commitment

One potential reason for the differences in performance within a social context may be the attribution of intentionality to the co-actor. There may be differences in the way people coordinate depending on whether a synchronisation partner is viewed as an intentional agent, who is firstly committed and intends to coordinate, and secondly is capable and will use similar mechanisms as themselves to synchronise. Several studies have demonstrated the effects of intentionality on various processes involved in joint action by using inanimate objects (Müller, Brass et al., 2011; Tsai & Brass, 2007), non-human agents (Tsai et al., 2008; Wykowska et al., 2016), and manipulations of the perceived level of behavioural intentionality of the interaction partner (Atmaca et al., 2011; Stenzel et al., 2012).

Additionally, a sense of the co-actor's commitment to achieving the joint goal may also affect performance (Michael et al., 2016a; Michael & Pacherie, 2015). The sense of mutual commitment between two or more people may be generated through explicit expressions of each co-actor's personal readiness to behave cooperatively (Gilbert, 1992), as well as implicit communicative cues (Bonalumi et al., 2019). When pursuing joint goals, a sense of commitment engenders expectations about another agent's contribution, leading to the establishment of a joint context. This joint context can facilitate coordination performance by encouraging a sense of joint-agency—a feeling of 'we' are conducting this task together, rather than 'I' am conducting this task alongside 'you' (Pacherie, 2014). This so-called 'we-agency' is argued to facilitate integration between representations of self and other, which may facilitate coordination of action timing (Bolt et al., 2016; Bolt & Loehr, 2017).

There is much evidence that an interaction partner's perceived commitment and intentionality lead to variations in performance (e.g. Atmaca et al., 2011; Green et al., 2019; Obhi & Hall, 2011a, 2011b; Tomasello & Carpenter, 2007). This finding suggests that when interacting with an intentional partner, individuals take into account their partner's goals and intentions and thus modulate their own performance based on this attribution. An additional aspect here in the way one accommodates an intentional partner's contribution is that the partner is 'like me' and will contribute by using similar processes and mechanisms to what oneself uses to achieve the joint goal (Hortensius & Cross, 2018; Müller, Brass, et al., 2011; Stenzel et al., 2012). This 'like me' quality has been associated with an increased tendency to co-represent and simulate others' actions (Stenzel et al., 2012; Tsai & Brass, 2007) and the use of one's own motor system to do so (Cross et al., 2006; Gallese, 2005; Liepelt et al., 2010; Liepelt & Brass, 2010).

1.4.1.3 Partner cooperativity

Another factor that may influence the way someone synchronises movement with another person in a musical context is the interaction partner's degree of skill or cooperativity. In the context of this thesis, cooperativeness refers to the partner's skill or competence—how well the partner is perceived as performing well in the joint task, rather than the willingness or compliance of the interaction partner. Partner cooperativity was investigated in two brain imaging studies conducted by Fairhurst et al. (2013, 2014). These authors employed the VP set to varying degrees of adaptivity to infer different levels of partner skill. In line with the results of Repp and Keller (2008), they found that synchronisation was optimal when the virtual partner was set to moderate degrees of adaptation that reflected levels typically found in humans. They also found that different brain regions were activated depending on the degree of cooperativity of the virtual partner. Midline structures associated with automatic self-referential and social processing were active when the VP was optimally adaptive, whereas right-lateralised regions associated with effortful cognitive control were active when the VP was an overly adaptive partner. Like these studies, the present program of research will employ the VP to simulate different degrees of responsiveness of synchronisation partners. This variation in partner responsiveness, under controlled experimental conditions, will inform to what extent the degree of difficulty to synchronise (reflecting the perceived level of partner skill) will modulate the underlying mechanisms of rhythmic interpersonal coordination.

1.4.1.4 Communicative cues

The agency of a co-actor may be demonstrated explicitly through direct communicative signals. However, may also be implied through more subtle behavioural cues that may lead to an implicit sense of a partner's capacity and willingness to coordinate (Poonian et al., 2015). When playing in ensemble, musicians may use verbal interaction to establish joint goals and evaluate progress towards these goals (Keller, 2014). During performance, musicians may also use a range of behavioural signals to explicitly communicate. For example, mutual eye gaze may be used as an indicator of joint attention (Davidson & Broughton, 2016; Khoramshahi et al., 2016; Tomasello & Carpenter, 2007), and body movements, such as head-nodding (Badino et al., 2014; Bishop & Goebl, 2018) are used to convey information about aesthetic intentions and to facilitate coordinated timing. These explicit cues directly demonstrate that a partner is committed and intends to coordinate and aids the development of a joint context.

In addition to these explicit signals, co-actor intentionality may be suggested at a more implicit level with subtle behavioural cues, such as whether the partner is responsive or not to the unfolding temporal dynamics of an interaction. A responsive partner that can flexibly modify their performance to facilitate joint timing implicitly conveys that they are an intentional agent who is committed to achieving the joint goal to coordinate. The importance of partner responsiveness has been demonstrated in several human-robot interaction studies. These studies have shown that feelings of rapport and the degree of interaction increases when humans are paired with contingently responsive robot partners rather than robots that are either non-responsive or respond randomly (Breazeal et al., 2016; Gratch et al., 2007; Kelso et al., 2009). Thus, the combination of both explicit communicative and implicit behavioural cues together may encourage the impression of an intentional co-actor.

1.4.2 Intrinsic factors

1.4.2.1 Social cognitive factors

It has been suggested that personality and general social cognitive ability may modulate the ability to coordinate action with others successfully. For example, people with better social competence and perspective-taking ability are better at predicting and matching others' behaviours (Kaplan & Iacoboni, 2006), leading to enhanced movement coordination. Schmidt et al. (1994) demonstrated that social competence was a factor that influenced interpersonal coordination. They found that dyads comprising one high social competence person and one low social competence person had higher stability in a coordinated pendulum swinging task than matched high or low competence pairs. This finding was interpreted as being due to better compatibility in these mixed pairs, with individuals higher in social competence taking on a leader role and those with low social competence taking on a follower role.

Synchronous musical performance involves a rapid and dynamic interchange of information. It is suggested that those who are better able to both read and communicate expressive intentions may have an advantage when coordinating musical behaviour (Overy & Molnar- Szakacs, 2009). Babiloni et al. (2012) suggest that empathic ability is one such social faculty that may underlie musical ensemble performance. This ability to accurately assess others' affective and cognitive states can enhance the prediction of others' behaviours, which in turn improves synchronisation performance. In support of this, Novembre et al. (2012) found that pianists with higher cognitive empathy displayed higher levels of motor control system activity whilst playing in a simulated social context. Likewise, Gazzola et al. (2006) found that those who scored higher in perspective-taking also recorded stronger activations of brain areas related to the auditory mirror system. Moreover, at an overt behavioural level, Novembre et al. (2019) found that dyads formed of two high perspective-taking participants performed with higher degrees of synchrony than dyads comprised of two low perspective-taking participants. Cognitive empathy, in particular perspective-taking, may thus facilitate interpersonal synchrony during musical joint action through supporting more accurate temporal predictions.

Another social cognitive factor that may affect interpersonal rhythmic coordination relates to individual differences in attitudes and preferences for interacting with other people. Humans differ in the degree to which they enjoy social interaction and engaging in tasks with other people. Such preferences relating to social interaction may result in a bias when interacting with different types of partners. Moreover, such biases may interact with the external social context to influence the mechanisms that support coordination and thus modulate synchronisation performance. For example, Varlet et al. (2014) found that those with high social anxiety had impaired synchronisation performance, particularly when required to take a leadership role. Thus, intrinsic social preferences can impact interpersonal coordination performance.

Many studies have shown an influence of biases (both explicit and implicit) on many aspects of behaviour, including social decision making (e.g. Rilling et al., 2008), reaction time (Tsai et al., 2011), and perceptual judgements (Molenberghs et al., 2013). For example, using EEG, Gutzell and Inzlicht (2010) observed increased neural activity over motor regions during observation of in-group members' actions reflecting co-representation, compared to when viewing out-group members' actions. These results suggest that simulation of others' actions is more likely for those considered to belong to one's in-group. Likewise, Müller, Kühn et al. (2011) demonstrated that people co-represent a partner's actions during a Social-Simon task to a greater degree when the co-actor is portrayed to have a matching skin colour to the participant, but not an incongruent skin colour. Together, these findings demonstrate that biases may modulate co-representation and performance within a joint action task. However, concerning rhythmic interpersonal coordination, little is understood about the influence of individual differences in social attitudes and partner preferences. Attitudes and preferences may interact with the perceived social context to modulate synchronisation performance with different partners. More specifically, the interaction of intrinsic and extrinsic social cognitive factors may affect the degree of self-other integration and segregation.

1.5 THESIS AIMS:

There has been much research into the role of various social factors during joint action in general. Similarly, the underlying core cognitive-motor skills that underpin rhythmic interpersonal coordination have been comprehensively investigated. However, how social factors influence rhythmic interpersonal coordination is yet to be established. As previously mentioned, joint musical performance is a highly refined form of joint action, and both intrinsic and extrinsic social cognitive factors may influence the way one anticipates and adapts during a rhythmic synchronisation task. The main aim of the current program of research is to examine the role that both extrinsic and intrinsic social factors may have on rhythmic interpersonal coordination performance and the core cognitive-motor skills that underpin this joint activity. Specifically, I investigate the role of social context, particularly the influence of both explicit and implicit cues relating to the intentionality of a co-actor on rhythmic interpersonal coordination. I also examine the role of individual differences in social preferences and how such intrinsic social cognitive factors modulate the effect of extrinsic social context. A summary of the sub-questions that comprise the overall research question is shown in Table 1.1.

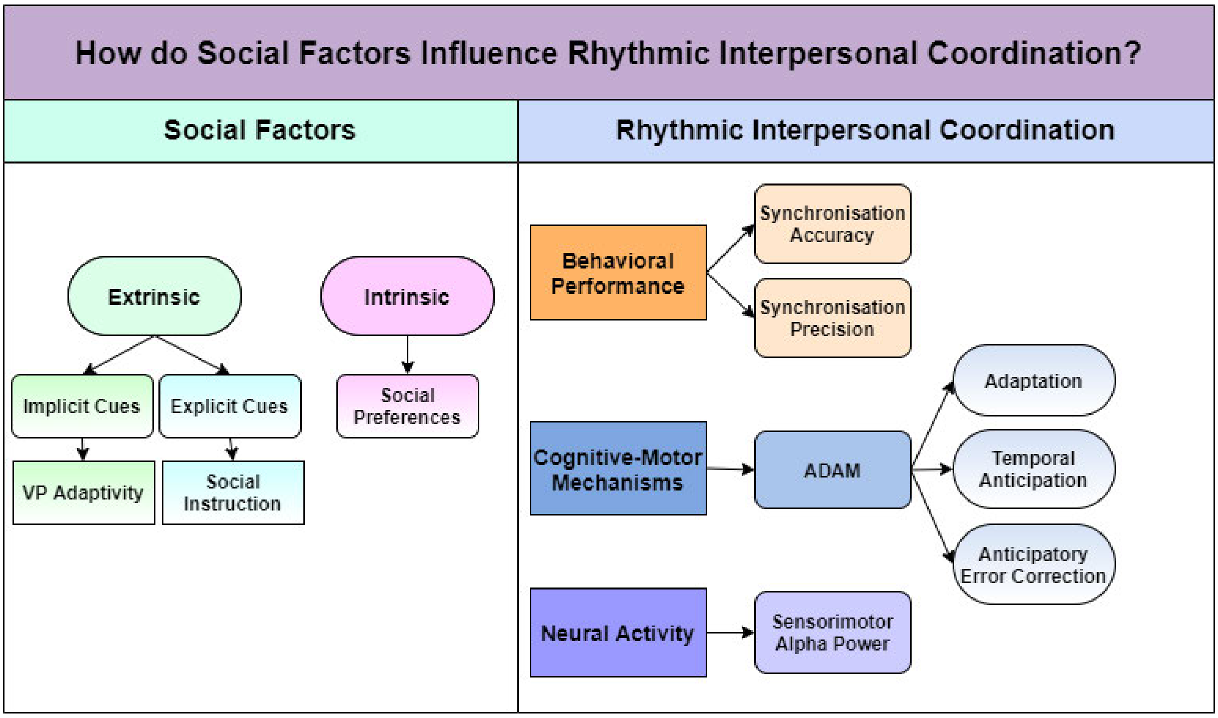
Table 1.1: Overview of Thesis Research Questions

Main Research Question	**How do social factors influence rhythmic interpersonal coordination?**
Question 1	How do extrinsic social factors influence rhythmic interpersonal coordination?
	A. How do implicit cues that imply an intentional and responsive synchronisation partner influence coordination?
	B. How do explicit cues that imply an intentional synchronisation partner influence coordination?
	C. Do these implicit and explicit cues interact?
Question 2	How do intrinsic social factors related to individual differences in partner preferences and social attitudes modulate the influence of extrinsic social factors?

To develop a comprehensive understanding of the effects of extrinsic and intrinsic social factors, I assess interpersonal rhythmic coordination at three levels of measurement—the level of behavioural performance, the underlying cognitive-motor mechanisms that support synchronisation (Experiments 1-3), and at the level of the brain (Experiment 3). At the level of behaviour, coordination performance is measured in terms of synchronisation accuracy and precision. In terms of the cognitive-motor mechanisms, the ADAM model of sensorimotor synchronisation is used to generate estimates of each participant's degree of adaptivity (period correction), temporal anticipation, and anticipatory error correction. Importantly, these parameters provide an approximation of participants' representations of self, of other, and the interplay between these self-other representations with the aim to better understand how social factors may differentially influence these representations between self and other, and more importantly, self-other integration and segregation. Finally, in experiment 3, the level of the brain is assessed in terms of EEG oscillatory activity. Specifically, oscillations within the alpha frequency band (~10 Hz) were observed over sensorimotor regions of the brain. This electrical activity was assessed to inform about the neural basis of co-representation during interpersonal coordination. An overview of the thesis design can be seen in Figure 1.6.

Throughout this program of research, extrinsic social factors were investigated by using both implicit and explicit cues to communicate the intentionality of the synchronisation partner. To do this, the VP was used as a synchronisation partner in a variety of contexts to assess the impact of extrinsic social factors on synchronisation performance in a controlled fashion. In all experiments, the degree of adaptivity employed by the VP acted as an implicit cue about the drumming partner's intentionality. The explicit cue, on the other hand, was manipulated in a variety of ways. In experiment 1, I manipulate the explicit task instructions to portray either a human drumming partner or a computer partner. In experiment 2, I employ an adaptive drumming humanoid robot programmed to be either a non-engaging robot whose only interaction was the drumming movement or to display explicit social cues designed to encourage social engagement. Finally, in experiment 3, to examine the neural underpinnings of synchronisation during social and non-social contexts, I use EEG to investigate the effect

Figure 1.6: Schematic of the thesis research aims



Note: The research aim of this thesis was to investigate the effect of extrinsic and intrinsic social factors on rhythmic interpersonal coordination performance and the cognitive-motor and neural mechanisms that facilitate coordination.

of partner intentionality on neural activity while drumming with the portrayal of either a human partner or a computer partner.

It was broadly hypothesised in all experiments that explicit and implicit cues relating to the intentionality of a rhythmic coordination partner would modulate rhythmic interpersonal coordination at multiple levels, including synchronisation performance, the underlying cognitive-motor mechanisms of synchronisation, and within sensorimotor brain activity. Such modulations in rhythmic coordination would suggest differences in the degree of co-representation and self-other integration that may occur with an intentional human partner, who is firstly committed to the joint goal, and secondly will employ similar mechanisms as oneself to synchronise. It was also hypothesised that any effects of extrinsic social factors might be modulated by individual differences in preferred synchronisation partner and beliefs about which partner is easier to synchronise with.

Chapter 2: Intentionality of a Co-actor Influences Sensorimotor Synchronisation with a Virtual Partner

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Note:
P.E. Keller is the first author’s primary supervisor.
C. J Stevens and G. Knoblich are on the first author’s supervisory panel.
B. Harry assisted with conceptual discussions of the computational modelling.

Chapter 2: Intentionality of a Co-Actor Influences Sensorimotor Synchronisation with a Virtual Partner

2.1 ABSTRACT

Interpersonal sensorimotor synchronisation requires individuals to anticipate and adapt to their partner's movement timing. Research has demonstrated that the intentionality of a co-actor affects joint action planning, however, less is known about whether co-actor intentionality affects sensorimotor synchronisation. Explicit and implicit knowledge of a synchronisation partner's intentionality may influence coordination by modulating temporal anticipation and adaptation processes. We used a computer-controlled virtual partner (VP) consisting of tempo-changing auditory pacing sequences to simulate either an intentional or unintentional synchronisation partner. The VP was programmed to respond to the participant with low or moderate degrees of error correction, simulating a slightly or moderately adaptive human, respectively. In addition, task instructions were manipulated so that participants were told they were synchronising with either another person or a computer. Results indicated that synchronisation performance improved with the more adaptive VP. Additionally, there was an influence of the explicit partner instruction, but this was dependent upon the degree of VP adaptivity and was modulated by subjective preferences for either the human or the computer partner. Beliefs about the intentionality of a synchronisation partner may thus influence interpersonal sensorimotor synchronisation in a manner that is modulated by preferences for interacting with intentional agents.

Keywords:
Interpersonal Coordination, Intentionality, Agency, Sensorimotor Synchronisation, Joint Action

2.2 INTRODUCTION

The ability to coordinate movement with others is a human quality often taken for granted. This ability can seem effortless; the way we time a handshake, clap hands in synchrony, or pass a ball to each other—all require little apparent cognitive effort. In fact, the ability to perceive another's actions and then match our own actions in space and time requires the combination of many perceptual, motor, cognitive and social processes (Konvalinka et al., 2010; Sebanz, Bekkering, et al., 2006). Previous studies have demonstrated that the mechanisms employed when completing a joint task in cooperation with another actor are different from those when completing a similar task alone. An important aspect of this effect is the knowledge that the co-actor is an intentional agent who means to cooperate in order to be successful in the joint task. However, little is known about the role of co-actor intentionality during synchronised movement, such as that enacted during musical ensemble performance. Interpersonal synchrony can be considered at several levels, for instance, the level of behavioural performance and the underlying sensorimotor mechanisms that support synchronisation, as well as at a broader social level, such as social cognitive factors and the social context. This study will investigate whether and how social context, specifically implicit and explicit cues of partner intentionality, affects both synchronisation performance and the mechanisms underpinning synchronisation.

2.2.1 The Role of Co-actor Intentionality

Joint action research has shown that when individuals perform an action in partnership with another person, their performance differs from when they perform the task alone (Obhi & Sebanz, 2011). This difference between solo and joint task performance has been attributed to the automatic tendency to form representations of a co-actor's actions and intentions, and to mentally simulate their movements (Sebanz et al., 2003). Moreover, the mere belief of the presence of an interaction partner can be sufficient to elicit a joint action effect. Several studies (e.g. Atmaca et al., 2011; Tsai et al., 2008) have found that by manipulating task instructions, so participants believed they were performing a task with an unseen other person—as opposed to alone or with a computer partner—resulted in modulation of task performance. These results suggested that participants formed representations about their apparent partner's actions, even though they were in fact never actually interacting with another person.

An important factor that is thought to contribute to the modulation of task performance during joint action is the knowledge that the interaction partner is an intentional agent—a partner that is perceived to be in control of their own actions and consequences and is capable of sharing the goal to complete a given task together. This has been demonstrated in several studies through the use of inanimate objects (Müller, Brass et al., 2011; Tsai & Brass, 2007), non-human agents (Wykowska et al., 2016), and manipulations of the perceived level of behavioural intentionality of the interaction partner (Atmaca et al., 2011; Stenzel et al., 2012). Variations in performance based on the perceived intentionality of an interaction partner suggest that individuals take into account their partner's goals, and thus modulate their own performance based on the belief their partner is not only intending to coordinate but will do so using similar processes to themselves to achieve the joint goal. This 'like me' quality has been associated with an increased tendency to co-represent others' actions (Stenzel et al., 2012; Tsai & Brass, 2007) and to use one's own motor system to simulate others' actions during social interaction (Gallese, 2005; Liepelt et al., 2010; Liepelt & Brass, 2010).

These studies of co-actor intentionality have generally used cooperative joint action tasks that assess the cognitive representations of stimulus-response mappings (e.g. the Social Simon task; see Sebanz et al., 2003). However, knowledge about co-actor intentionality may also affect sensorimotor processes that underpin behaviour in tasks requiring real-time interpersonal coordination, as in musical ensemble performance. Experienced music and dance ensembles demonstrate exceptional interpersonal coordination, achieving remarkable temporal precision while also remaining flexible during dynamic conditions. Furthermore, ensemble performance, by definition, occurs in an interpersonal setting, and social factors such as the intentionality of an interaction partner may therefore also affect the quality of rhythmic coordination (Davidson & Broughton, 2016; Keller, 2014). Such influence has been demonstrated by Kirschner and Tomasello (2009), who found that children's performances improved in a joint drumming task when in a social context, as opposed to drumming with either a drumming machine or a pre-recorded beat. Similarly, at the level of the brain, Novembre et al. (2012) found higher excitability of the motor system when participants believed they were playing a piano piece with another person, instead of in a solo situation, indicating more activation of neural networks that may be involved in motor prediction during joint action. These studies indicate that the joint nature of a task may modulate performance (however, see Welsh et al., 2007, for a contrary finding). However, these studies do not directly assess if it is the intentionality of the coordination partner that is the modulating factor.

The attribution of a co-actor's agency may be both explicit and implicit (Poonian et al., 2015). The knowledge that the partner is an intentional agent and overt instructions to coordinate may give rise to an *explicit* belief of a partner's intentionality (as was manipulated in the above studies). At the same time, behavioural cues reflecting how responsive a co-actor is may elicit an *implicit* sense of a partner's intention to coordinate. For example, in human-robot interaction studies, it has been found that non-verbal communicative cues that are contingent on the human co-actor's behaviour can lead to robots being perceived as intentional social beings (Breazeal et al., 2016; Gratch et al., 2007; Mutlu et al., 2009).

Such attribution of intentionality may arise due to the activation of brain regions involved in social-cognitive processing. In a synchronised finger-tapping study investigating the brain bases of dynamic real-time coordination, Fairhurst et al. (2013) employed a virtual partner (VP)—an interactive auditory pacing sequence—set to varying degrees of adaptivity which simulated various levels of cooperativity. The results indicated that distinct neural networks were recruited in response to differences in VP cooperativity. Synchronisation with optimally adaptive VPs, which was stable and judged to be low in difficulty, resulted in activation of midline structures associated with social processes. By contrast, overly adaptive VPs, which yielded less stable performance and higher difficulty judgments, were associated with right-lateralised cognitive control networks. These findings suggest that optimally adaptive, cooperative partners may lead to implicit judgements of partner agency and the intention to coordinate and that the perceived difficulty of the interaction may influence such attributions.

In sum, social factors are an important consideration when investigating interpersonal synchrony. Factors relating to the perceived interaction partner, such as agency and intentionality, may affect coordination performance by influencing the operation of basic mechanisms that support sensorimotor synchronisation. These basic mechanisms include a combination of adaptive and anticipatory processes that may be each affected differentially by judgements of partner intentionality.

2.2.2 Mechanisms underpinning interpersonal synchronisation

Previous sensorimotor synchronisation research has found that collaboration between adaptive and anticipatory processes is what allows people to temporally coordinate actions in a precise yet flexible manner (Keller et al., 2014; Mills et al., 2015; van der Steen & Keller, 2013). Individuals continuously monitor the joint outcome and adapt their movements to correct for timing errors or accommodate tempo changes while simultaneously anticipating what is about to happen in upcoming actions of both self and other. Adaptive timing mechanisms make compensatory adjustments to movement timing in order to minimise interpersonal asynchronies, whereas temporal anticipation enables the prediction of when a partner's upcoming actions will occur. Both processes have been extensively studied in the context of sensorimotor synchronisation tasks that require participants to tap a finger or strike a drum in time with auditory pacing sequences (for reviews, see Repp, 2005; Repp & Su, 2013).

Adaptive timing can be implemented as one of two types of error correction, phase and period correction, which each serve to reduce asynchronies between movements and pacing events during sensorimotor synchronisation. Phase correction is an automatic process that occurs without the conscious awareness of asynchrony and compensates for temporal deviations continuously by adjusting the timing of each movement based on a previous asynchrony, while leaving the rate of an underlying internal timekeeper unchanged (Repp, 2001, 2005). Period correction, on the other hand, is an intentional adjustment of the rate of the internal timekeeper in response to the conscious perception of a tempo change in the pacing sequence (Repp, 2005; Repp & Keller, 2004).

In musical ensemble performance, adaptive timing is simultaneously employed by multiple individuals, each responding to interpersonal asynchronies by adjusting his or her own subsequent actions via temporal error correction (e.g., Goebl & Palmer, 2009; Jacoby et al., 2015; Wing et al., 2014). To investigate such mutual adaptation under controlled conditions, Repp and Keller (2008) employed a computer-controlled VP. The VP works by using a mathematical algorithm that enables the auditory pacing sequence to implement error correction (see Mates, 1994; Repp & Keller, 2004; Vorberg & Schulze, 2002, for details) and thus 'interact' with a participant in a manner simulating an adaptive human partner.

When employing error correction during a tapping synchronisation task with a human participant, the computer-controlled VP is programmed to respond to an asynchronous tap by altering the timing of its next tone to account for a proportion of the asynchrony. For example, if the participant taps too early compared to a VP-produced tone, the VP will respond by adjusting the timing of its next tone to sound earlier. The degree to which the VP corrects for timing errors can be prescribed and manipulated such that the computer may simulate either a responsive synchronisation partner (e.g., by employing a moderate degree of phase correction) or a less responsive partner (by employing a lower amount of phase correction). Several empirical studies (e.g., Fairhurst ety al., 2013; Mills et al., 2015; Repp & Keller, 2008) have demonstrated that moderate levels of VP adaptivity are best for optimal performance (lower overall asynchrony and variability). By virtue of the VP being more responsive, the more adaptive VP may provide an implicit cue that it is an intentional agent who means to mutually coordinate in order to achieve the joint goal of synchronised timing.

In contrast to adaptive timing, which acts in a retrospective fashion to maintain coordination, temporal anticipation allows for accurate prediction of others' future actions. In music performance, temporal anticipation entails the prediction of tempo variations that performers introduce to communicate musical structure, emotion, and aesthetic intentions (Keller et al., 2016). Consistent with claims that action prediction recruits the observer's motor system (Aglioti et al., 2008; Kilner et al., 2004; Wilson & Knoblich, 2005), it has been argued that the prediction of expressive tempo changes involves action simulation, auditory imagery, and working memory (Colley, Keller, et al., 2018; Keller, 2012; Keller et al., 2007; Pecenka et al., 2013). Individual differences in these capacities lead to inter-individual variation in anticipatory ability, with some individuals being proficient at predicting tempo changes while others tend to follow or 'track' these changes (Michon, 1967; Mills et al., 2015; Pecenka & Keller, 2009, 2011; Rankin et al., 2009).

To further understand adaptation and temporal anticipation and how these mechanisms interact, van der Steen and Keller (2013) developed the ADaptation and Anticipation Model (ADAM). This computational model consists of three modules that include parameters representing (1) adaptive processes, (2) anticipatory processes, and (3) a 'joint internal model' that integrates the adaptive and anticipatory processes. While traditionally studied separately, recent research indicates that temporal adaptation and anticipation are linked. Mills et al. (2015) found a positive correlation between behavioural estimates of temporal error correction and temporal anticipation, suggesting that adaptive mechanisms used to correct one's own subsequent movement timing interact with anticipatory mechanisms used to predict other's movement timing. This interaction is instantiated in ADAM's joint module as a process of anticipatory error correction, which involves an adjustment of the timing of planned movements to correct potential synchronisation errors before they occur (van der Steen & Keller, 2013). Specifically, the joint module compares the planned timing of one's next movement (generated by the adaption module) with the predicted timing of a synchronisation partner's movement (generated by the anticipation module) and corrects a proportion of any anticipated discrepancy. To the extent that the joint module provides a seat where planning for self and predictions of other are integrated to enable anticipatory error correction (Keller et al., 2016), this module may be susceptible to the influence of beliefs concerning the perceived intentionality of an interaction partner.

2.2.3 Present study

The present study uses a virtual drumming partner to investigate the role of social context on synchronisation performance and the mechanisms underlying interpersonal synchronisation. Specifically, the effect of both explicit and implicit cues relating to the intentionality of a synchronisation partner was investigated in relation to the mechanisms of adaptive timing (period correction), temporal anticipation, and the interaction between the two (anticipatory error correction). To this end, we explicitly instructed pairs of participants to synchronise drumming with each other (i.e., an intentional human partner) or with a computer-generated, tempo-changing sequence of sounds (a deterministic, unintentional partner). In reality, we employed an adaptive VP in both conditions. Thus, when participants are instructed to believe they were coordinating with a human partner, they were, in fact, drumming with the VP.

We also provided an implicit cue as to the partner intentionality by varying the degree of adaptivity (phase correction) implemented by the VP to create ‘low adaptivity’ and ‘moderate adaptivity’ partners. To the extent that the VP is more responsive and thus ‘cooperative’ when employing a moderate amount of error correction (Fairhurst et al., 2013), the moderately adaptive partner implies a more intentional partner. These differences in the degree of adaptivity are generally not explicitly detectable and thus represent an implicit cue of the partner’s intention to coordinate. While increased adaptivity could also reflect better ability to synchronise, we manipulated the responsiveness of the VP within-subjects, with all participants experiencing both the low and moderately adaptive versions for each of the instructed ‘partners’. This design was to ensure that the higher adaptivity of the VP was not viewed as a partner with a better ability to synchronise but rather an increase in responsiveness or intention to coordinate. As the two levels of adaptivity were experienced with each partner, it is presumed that the change in partner responsiveness was perceived not as a result of a change of ability but rather a change in the intention or commitment to synchronise.

It was hypothesised that performance would be better (reflected in smaller, less variable asynchronies) when participants were told that the VP was a human partner (explicit intentionality cue) and is moderately adaptive (implicit intentionality cue). This effect was expected to be attributable to modulations in the degree of temporal anticipation and anticipatory error correction (as reflected in parameter estimates for the anticipation and joint modules of ADAM, respectively). Assuming that cooperation implies intention and commitment to achieving the joint goal (Michael et al., 2016a, 2016b; Michael & Salice, 2017), we predict that more effort will be invested into temporal anticipation and anticipatory error correction if the participant believes that they are interacting with an intentional human partner who is especially cooperative.

The rationale for expecting modulations of temporal anticipation is that interacting with an intentional agent can encourage increased simulation of the partner's actions (Liepelt et al., 2010; Liepelt & Brass, 2010), simulation facilitates anticipatory processes (Aglioti et al., 2008; Kilner et al., 2004; Novembre et al., 2014), and anticipation leads to better coordination with tempo-changing sequences (Pecenka & Keller, 2009, 2011). Therefore, the increased simulation should allow more accurate prediction (reflected in higher anticipation parameter estimates) and hence better synchronisation when participants believe that the VP is another human. Furthermore, the belief that the partner is 'like me' (human rather than a computer) may encourage tighter integration of self and other (Gallese, 2005), leading to an increase in anticipatory error correction parameter estimates in ADAM's joint module.

It was unclear whether partner intentionality would affect temporal adaptation, specifically parameter estimates of period correction. On the one hand, period correction is an intentional process and may be boosted through increased attentional resource allocation (see Repp & Keller, 2004) if the synchronisation partner is perceived to be 'like me' from the participant's perspective. On the other hand, period correction is a basic requirement in synchronisation with tempo changes and may not be affected by beliefs about the source of the pacing signal if the sequence contains tempo changes, and the participant aims to perform the task as accurately as possible.

A secondary question was whether individual differences in perceived difficulty to synchronise with each partner would modulate the effect of partner intentionality. We were particularly interested in participants' subjective experiences of interacting with the VP when they were instructed that it was a human versus a computer, as differential preferences or perceptions of the interaction with one type of partner over the other may lead to asymmetrical effects of perceived intentionality. Accordingly, behavioural performance and ADAM parameter estimates may be relatively high in the condition that the participant prefers. Such a finding would add to a growing body of evidence that social-cognitive factors impact upon the mechanisms underlying interpersonal synchronisation (see also Fairhurst et al., 2014; Novembre et al., 2012, 2014).

2.3 METHOD

2.3.1 Participants

A total of 64 participants took part in the study (48 females; *M* =23.3 years, *SD* = 8.06). Fifty-two were undergraduate psychology students from Western Sydney University who participated in return for course credit, and 12 were volunteers who were recruited from the greater Western Sydney area. Fifteen participants had 5 years or more musical experience (*M* = 11.33years, *SD* = 9.27years), however the majority had little to no musical experience (*N* = 49, *M* = .5years, *SD* = 1.13years). Participants who recorded insufficient drumming data (*N* = 13; See Data Analysis for exclusion criteria) were excluded. This was mainly due to the equipment not registering drum strokes that did not have sufficient force and is commensurate with other sensorimotor synchronisation studies (e.g. Mills et al., 2015). Additionally, participants who guessed the true nature of the experiment in a post-experiment interview (*N* = 7) were excluded, leaving 44 participants in the final sample. The experiment was approved by the university's human research ethics committee, and all participants provided informed written consent. To avoid disclosure of the true nature of the experiment to other participants during the data collection phase, participants were debriefed in an email after the conclusion of data collection and were given the option to withdraw their data, which was not requested by any participants.

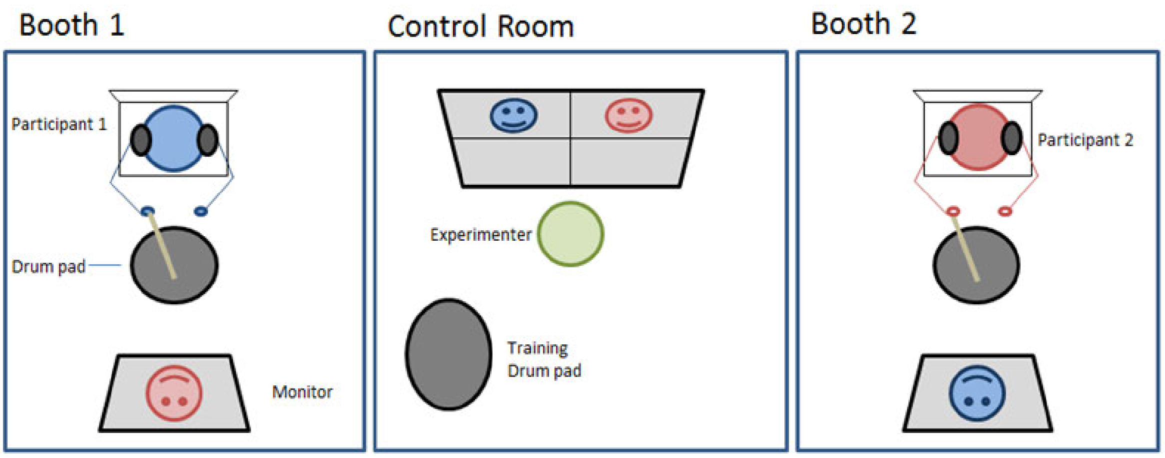
2.3.2 Design

A two-step study design was used, where the first step involved an experimental manipulation of explicit and implicit cues relating to partner intentionality and the second step introduced a post-test measure of subjective partner preference as a covariate. One of the experimental independent variables was the explicit Social Instruction, where participants were instructed to synchronise with either a human interaction partner or a sequence of tones generated by a computer (in reality, the participants were always synchronising with the VP). The second experimental independent variable was the VP Adaptivity, with the degree of adaptivity being either low or moderate, which was an implicit cue as to the intentionality of the partner. A third between-subjects variable was introduced based on the participant's subjective experience of which social condition was easiest. After data collection was completed, participants were divided into three groups depending on whether they reported having found it easier with the 'human' partner, the 'computer' partner, or if they found the conditions to be the same. It was assumed that the condition participants deemed the easiest would reflect the condition they were most successful in, in regard to synchronisation performance. Based on this, we operationally defined this subjective judgement as 'Partner Preference' within this paper. The dependent measures comprised of behavioural measures of synchronisation accuracy (mean absolute asynchrony) and stability (SD of asynchrony, inversely related to stability); as well as modelling estimates from ADAM of each participant's anticipatory and adaptive tendencies—namely period correction, temporal anticipation, and anticipatory error correction.

2.3.3 Materials

There were two identical drumming set-ups in two soundproof booths that were adjacent to a central control room (see Figure 2.1). In each booth, the drums were placed in front of Cueword teleprompter that was part of a dual video set-up. A video camera was attached to the back of each teleprompter to record each participant, which allowed the experimenter to view and record both participants from the control room and for the participants to see each other via a live feed through each teleprompter at specified times. In addition, a Beyerdynamic condenser shotgun microphone allowed a live audio feed, and an Australian Monitor 10W speaker in each booth allowed the experimenter to communicate verbally with the participants and for the participants to communicate with each other at specified times. The experimenter used an AMX Modero Wired G4 Touch Panel to control the audio and video feeds to regulate when participants could see and hear each other throughout the experiment. All audio and video footage were recorded on Grass Valley Turbo-1 iDDR recording units.

Figure 2.1: Schematic of the experimental setup.



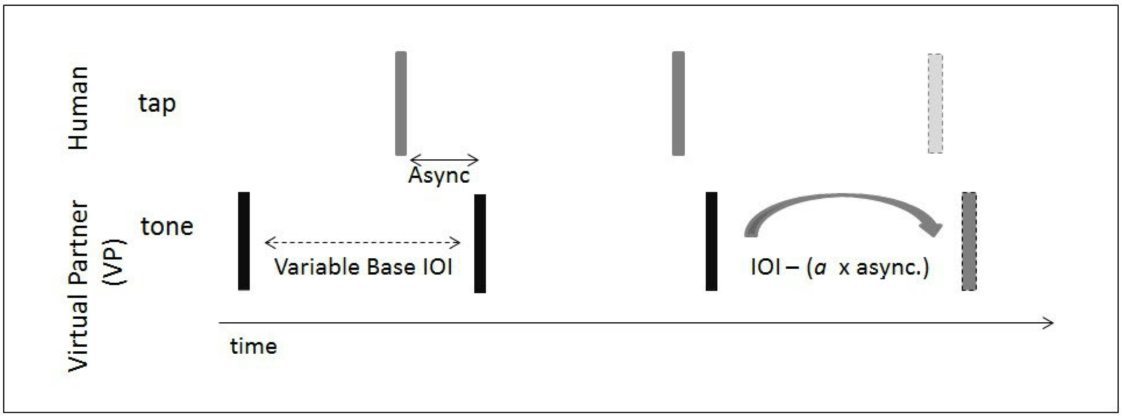
Participants each used a wooden drumstick with a nylon tip to drum on Yamaha DTX TP70S drum pads, which were held on a metal drum stand in front of the participant. The drum pads were each connected to Roland TD-9 Percussion Sound Modules that were connected to Motu Microlite MIDI interfaces. These were in turn connected to Acer laptops running windows software. A custom-made C++ program recorded the tapping data as well as presenting the auditory stimuli, which were delivered through Sennheiser HD650 headphones connected to each of the laptops. End to end latency measures that were taken prior to the experiment revealed a mean delay of 60ms (*SD* = .9ms), which was taken into account by the program. Participants completed initial training and practice trials on a Roland Handsonic 10 percussion pad.

2.3.4 Stimuli

The stimuli were auditory sequences of percussion sounds. Each sequence started with four synthesised cowbell tones, followed by 60 synthesised woodblock tones with clear onset and decay. A beep indicated the end of the trial. The sequences progressed through tempo variations that accelerated and decelerated following a sinusoidal function (as in Mills et al., 2015; Pecenka et al., 2013; Pecenka & Keller, 2011). These sequences varied between 500 and 600ms, with step sizes varying between 1 and 32ms. This pattern of variation in the sequences was chosen to reflect tempo changes observed during expressive timing in musical performance, and were additionally realistic patterns that could be produced by a non-expert human partner.

In addition to these tempo variations, the adaptive function of the virtual partner was applied to implement second-order phase correction (see figure 2.2). This adaptive function simulates human phase correction processes by correcting the timing of the subsequent sound by a proportion of the asynchrony between the second-to-last tone and the corresponding tap (see Repp and Keller, 2008).

Figure 2.2: Overview of the adaptive timing mechanism of the virtual partner.



Note: Second-order phase correction alters the timing of the subsequent inter-onset interval (IOI) by adjusting for a proportion (α) of the asynchrony (async.) between the second-to-last pacing event and corresponding drum tap.

Two levels of adaptivity were used, α= .1 (low adaptivity), and α= .4 (moderate adaptivity), with each value representing the proportion of asynchrony between the tone and the drum tap in the second to last event that was corrected for in the subsequent event. A linear phase correction model based on Vorberg and Schulze (2002) controlled this process with the algorithm:

$$t_{n+1} = t_n + T + a_c \times async(t_{n-1})$$

where t_n = time of pacing event, T = base Inter-Onset Interval (IOI; drawn from the tempo changing sequence), a_c = phase correction parameter implemented by the computer (.1 or .4), and async = asynchrony between tap and pacing event. For example, if a participant tapped too early (a negative asynchrony) compared to a tone, the second successive event would then occur earlier by a proportion (.1 or .4) of that asynchrony. Thus, each IOI throughout the tempo changing sequence was adjusted in response to the amount and direction of the second to last tap's asynchrony. The present study differs from previous studies that employed the VP in the sense that the current VP algorithm implements second-order, rather than first-order, phase correction[1].

2.3.5 Procedure

Participants were randomly paired based on the availability of experimental sessions and participant schedules, with both participants arriving and being instructed together. They were informed that the purpose of the experiment was to examine how well two people could synchronise with each other whilst drumming with only auditory information. The participants were shown the two separate rooms and told that their task was to drum in time with each other for half of the experiment, and then, in order to establish a baseline, they would drum in time with just a sequence of sounds from the computer for the other half of the experiment (counterbalanced). In reality, participants were always drumming with the VP

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[1] Previous research on phase correction has found evidence that second-order phase correction supplements first-order correction under certain conditions in sensorimotor synchronisation tasks, including at relatively fast tempi (Repp et al., 2012; Semjen et al., 2000) and with high task demand and expertise (Pressing, 1998). Pilot testing revealed that synchronising with sequences that are both adaptive and include tempo-changes qualifies as a demanding task and, furthermore, that the tendency for participants to 'overshoot' at tempo-change transitions (fast-to-slow and slow-to-fast turning points) raises questions about whether first-order correction is the best option at these points. In any case, to justify the use of second-order phase correction in the present experiment on empirical grounds, we conducted an additional experiment (Mills & Keller, in prep.) to compare the effects of first-order versus second-order phase correction on behavioural performance and parameter estimates obtained for sensorimotor synchronisation with tempo-changing VPs. This additional experiment revealed that, while the SD of asynchronies was higher for sensorimotor synchronisation with VPs that implemented second-order correction than for first-order correction (as could be predicted based on Vorberg & Schulze, 2002), all other measures including the parameter estimates of interest in the present experiment were commensurate for first-order and second-order correction. We therefore expect that results would generalise to contexts where first-order correction is employed.

algorithm, and the drumming tasks were identical during each of the different partner instruction conditions.

Before the experimental trials commenced, the participant pairs completed three practice trials together in the central control room, where they both drummed simultaneously on a single drum pad in time with a sequence of sounds played through a loudspeaker. These sequences were identical to the tempo changing sequences used during the experimental trials (see Stimuli); however, there was no VP phase correction applied (α= 0). The participants were asked to note the variation in tempo and were asked to replicate these variations when they were later drumming with each other. Participants were then seated in their respective booths and the doors closed. To reinforce that there was another person doing the experiment, initially, the dual video set up would allow participants to see and hear each other while the experimenter gave further instructions. This visual and auditory information was turned off during the experimental blocks so that the participants could only hear the auditory stimuli from the computer through their headphones.

Participants completed four blocks of drumming, with each block containing 12 sequences of 60 tones (see Stimuli for details). They were instructed that two of these blocks were baseline recordings where participants would be drumming in time with a computer-generated sequence of sounds, and the other two blocks were joint drumming trials where participants would be drumming with their human partner. For the two blocks within each Social Instruction condition, the VP implemented low adaptivity (α= .1) during one block and moderate adaptivity (α= .4) during the other. The order of these blocks was counterbalanced and alternated between each condition, with the experimenter informing the participants at the beginning of each block whether they were drumming with their human partner or with the computer. In reality, participants were drumming with the VP during all four blocks.

To reinforce the notion that the drumming task was being completed with a human partner, participants completed a joint problem-solving task between each drumming block. Participants were each given a 5 x 5 grid containing 25 pictures of items in random order. Each grid contained four items that the other participant did not have. By only talking to each other through the speakers in the booth, participants were asked to identify the eight differences between their grids as quickly and accurately as possible. A different set of pictures was used each time the participants completed this task (three times in total). This task was included only as a ruse to maintain the illusion of the joint context, and performance data for this task were not analysed.

After all drumming tasks were completed, participants were given a questionnaire to assess whether they believed the experimental instructions and to probe which conditions the participants found easier by including a forced-choice question (with response options of ‘When I was drumming with my partner’, ‘When I was drumming with the computer’ or ‘It was the same’). Given that participants were interacting with a computer-controlled VP in all conditions, and that all conditions were identical in objective difficulty, this question was assumed to probe subjective preferences for interacting with a human or computer partner. While preferences are not necessarily related to how easy a task is, in the context of a basic synchronisation task, we assume that the partner that is ‘easier’ to synchronise with is the preferred partner. We thus operationally define this judgement of task ‘easiness’ to reflect subjective preferences for interacting with either a human or computer partner.

2.3.6 Data Analysis

Data were initially screened for missing taps in Microsoft Excel, and linear interpolation was used to fill gaps left by missing taps and to replace taps that produced a large asynchrony (defined as an asynchrony of > ± 250ms, which represents half of the smallest target IOI in a sequence). Trials that were missing > 3 taps or included three consecutive missing taps were excluded from the analysis. Participants who had four or more trials excluded out of the 12 trials in each condition were removed from the analysis. This criterion ensured that there was sufficient data to generate robust estimates in ADAM.

Data were then processed using MATLAB to obtain measures of synchronisation performance and to generate parameter estimates of period correction, temporal anticipation, and anticipatory error correction using ADAM. Synchronisation performance was assessed in terms of accuracy (mean absolute asynchrony) and stability (SD of signed asynchronies). Asynchrony was calculated by subtracting the onset time of the current tap from the onset time of the current tone. Mean absolute asynchrony and SD asynchrony were calculated for each individual trial and then averaged across all trials of the corresponding type. Before averaging, a log transformation was applied to absolute asynchronies in each of the four conditions to correct for violations of normality.

Parameter estimates were generated using the version of ADAM ('Joint ADAM Beta') that van der Steen, Jacoby, Fairhurst, and Keller (2015) found to have the best fit to empirical data for sensorimotor synchronisation with tempo-changing sequences. In this version of ADAM, the adaptation module includes a parameter for period correction (β), the anticipation module contains a parameter for temporal anticipation (δ), and the joint module, which connects the anticipation and adaptation modules, contains a parameter for anticipatory error correction temporal anticipation (δ), (see van der Steen et al., 2015 for details).

The adaptation module estimates an individual's period correction based on a linear autoregressive error correction model whereby an adjustment is made to the period of the internal timekeeper by a proportion (β) of the most recent asynchrony. The anticipation module generates predictions about the timing of upcoming tones based on the weighted sum of both predictive (extrapolation based on the two previous IOI intervals) and tracking (repeating the previous IOI) processes. An anticipation estimate (δ) of .5 represents that equal prediction and tracking is occurring, whereas values greater than .5 represent relatively more prediction than tracking and values less than .5 represent relatively more tracking behaviour. Finally, ADAM's joint module engages in anticipatory error correction by comparing the output of the adaptation module and the anticipation module and correcting for a proportion (γ) of the asynchrony between the next planned movement and the next predicted sound. When γ is 0, the planned next movement is driven purely by the output of the adaptation model, while the closer γ is to 1, the greater the correction incorporates the output of the anticipation module (the more influence the prediction of the other's timing has over the planned timing of the next movement). Estimates of each model parameter from ADAM were obtained for each participant by fitting the model to the empirical behavioural data from each trial using a bounded Generalised Least Squares method (see Jacoby et al., 2015; van der Steen et al., 2015). These parameter estimates were then averaged across corresponding trials for each participant.

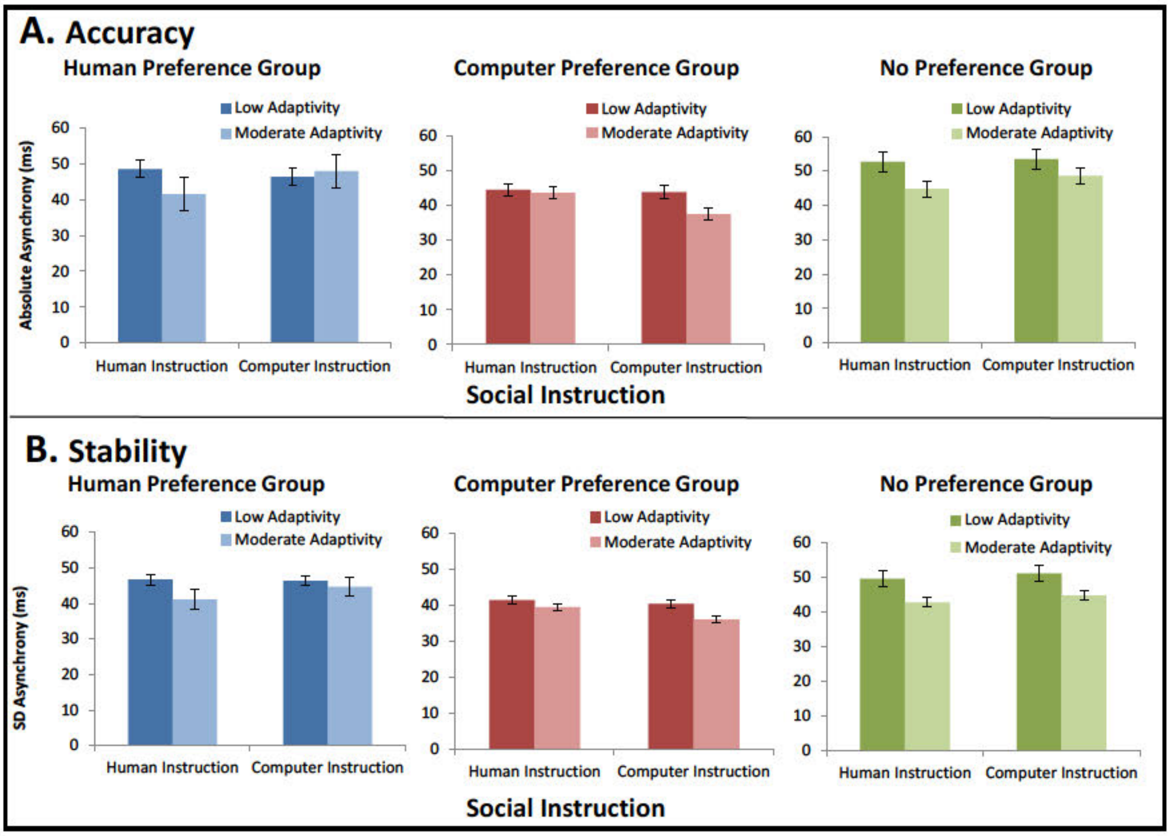
2.4 RESULTS

To investigate the effect of the experimental manipulations of Social Instruction (human vs computer partner) and VP Adaptivity (low vs moderate adaptivity), as well as the between-subjects factor based on participants' preferences for partner type (prefer human partner, prefer computer partner, no preference), a series of factorial (2 x 2) x 3 Analyses of Variance (ANOVA) were conducted on each of the dependent measures: mean absolute asynchrony, SD asynchrony, period correction (β), temporal anticipation (δ), and anticipatory error correction (γ) estimates. The between-groups factor of Partner Preference was inferred from responses to a post-test questionnaire that assessed subjective judgements of which condition was easiest. The questionnaire revealed that while some participants rated that there was no difference in preferences between the two Social Instruction conditions (n=17), some preferred the apparent human partner (n=10), while others preferred the computer partner (n=17). Prior to these analyses, a preliminary ANOVA on each dependent measure revealed that there was no significant effect of condition order, and no significant relationship between the order of presentation for the Social Instruction condition and judgement about which condition was preferred. The assumption homogeneity of variance was met, and all effects are reported as statistically significant at $p < .05$.

2.4.1 Synchronisation accuracy and stability

Contrary to our main hypothesis, the analysis of log-transformed mean absolute asynchrony (Figure 2.3A, shown untransformed) revealed that there was no significant main effect for Social Instruction, $F(1,41) = 0.10$, $p = .92$, $\eta_p^2 < .001$. The belief that one is interacting with a human rather than a computer did not reliably increase overall synchronisation accuracy. There was, however, a significant main effect of VP Adaptivity, $F(1,41) = 22.66$, $p < .001$, $\eta_p^2 = .356$, with the low adaptivity condition displaying higher asynchrony than the moderate adaptive condition, suggesting better overall joint performance when the VP more adaptive. There was no main effect of Partner Preference $F(2,41) = 1.22$, $p = .31$, $\eta_p^2 = .056$, and no significant interaction between Social Instruction and VP Adaptivity, $F(1,41) = 1.92$, $p = .17$, $\eta_p^2 = .272$. However, the two-way interaction between Social Instruction and Partner Preference approached the conventional threshold for statistical significance, $F(2,41) = 3.22$, $p = .05$, $\eta_p^2 < .136$, and a significant three-way interaction between VP Adaptivity, Social Instruction, and Partner Preference, $F(2,41) = 4.92$, $p = .012$, $\eta_p^2 = .193$ (see Figure 2.3). As Partner Preference was included as a post-hoc variable, we also conducted a Bayesian analysis (calculated using JASP software, Version 0.8.6) to test the integrity of this interaction. The Bayes factor for the full model, including the three-way interaction, was BF10 = 15.538, whereas the Bayes factor for a model without the interaction term included was BF10 = 6.829. The inclusion Bayes factor based on matched models that directly compare these two models was 2.275, which can be interpreted to indicate that the data are more than twice as likely under a model with this interaction term as under a model without this interaction term.

Figure 2.3: Mean synchronisation performance



Note: Measures of synchronisation performance split between low VP Adaptivity and moderate VP adaptivity for the three partner preference groups. Panel A – Accuracy (Mean Absolute Asynchrony, untransformed) and Panel B - Stability (SD Asynchrony). Error bars represent SEM as calculated using the repeated measures method suggested by Franz and Loftus (2012)

These interactions were unpacked by performing analyses separately for each Partner Preference group. A series of one-tailed dependent t-tests were conducted to compare synchronisation accuracy between the two levels of adaptivity for each of the different social instruction conditions. One-tailed tests were chosen because of the directional hypothesis that performance accuracy would improve (lower asynchronies) in the moderately adaptive condition compared to the low adaptivity condition. For the human preference group, accuracy was significantly better when drumming with the moderately adaptive partner only during the human instruction condition, $t(9) = 2.04$, $p = .036$, $d = .64$ and not when instructed that the partner was a computer, $t(9) = -.47$, $p = .676$, $d = -.15$. Likewise, the computer preference group showed significant improvement in accuracy with the moderately adaptive partner only during the computer partner instruction, $t(16) = 3.99$, $p < .001$, $d = .97$, and not the human partner instruction, $t(16) = .80$, $p = .22$, $d = .20$. Whereas the no preference group showed significantly higher accuracy with the moderately adaptive partner during the human instruction condition, $t(16) = 4.52$, $p < .001$, $d = 1.10$ and approached significant improvement during the computer instruction condition, $t(16) = 1.71$, $p = .053$, $d = .42$.

The analysis of the SD asynchrony (Figure 2.3B) revealed no significant main effect of Social Instruction, $F(1,41) = 0.19$, $p = .66$, $\eta_p^2 = .005$, a significant main effect of VP Adaptivity, $F(1,41) = 26.40$, $p < .001$, $\eta_p^2 = .39$ with the low adaptivity condition displaying greater variability than the moderate adaptivity condition), and no main effect of Partner Preference, $F(2,41) = 2.57$, $p = .09$, $\eta^2 = .111$. There were also no significant interactions (all $p > .05$), however, the general trend for the data reflected that found in the accuracy data (see Figure 2.3B).

2.4.2 Model-based parameter estimates of underlying mechanisms.

All model-based parameter estimates are presented in table 2.1. There were no significant effects (all $p > .05$) in the analysis of period correction (β), which indicates that temporal adaptation was applied similarly across all conditions. For the anticipation parameter (δ), the estimates were quite low overall. Given that a value of 0.5 indicates an equal amount of predicting and tracking, the relatively low observed values indicate that participants had a stronger tendency to track rather than to predict the tempo changes in all conditions. The ANOVA on anticipation estimates revealed no significant effect of Social Instruction, $F(1,41) = 0.55$, $p = .461$, $\eta_p^2 = .013$ but there was a significant effect of VP Adaptivity, $F(1,41) = 7.33$, $p = .01$, $\eta_p^2 = .152$, with the moderately adaptive condition associated with more tracking/less predictive behaviour than the low adaptivity condition. There was no significant main effect of Partner Preference, $F(2,41) = .60$, $p = .56$, $\eta^2 = .028$, nor were there any significant interactions (all $p > .05$).

Table 2.1: Average parameter estimates generated by the ADaptation and Anticipation Model (ADAM) for Period correction (β), Anticipation (δ), and Anticipatory error correction (γ) for the Social Instruction and VP Adaptivity conditions for each Partner Preference group.

Condition			**Parameter Estimates**					
Preference Group	**Social Instruction**	**Adaptivity**	**Period Correction**		**Anticipation**		**Anticipatory Error Correction**	
			M	***SE***	***M***	***SE***	***M***	***SE***
Human preference ($n = 10$)	Human	Low	0.114	0.036	0.052	0.020	0.616	0.051
		Moderate	0.098	0.022	0.042	0.022	0.630	0.048
	Computer	Low	0.125	0.027	0.056	0.024	0.620	0.054
		Moderate	0.099	0.023	0.050	0.024	0.564	0.054
Computer preference ($n = 17$)	Human	Low	0.175	0.041	0.061	0.021	0.677	0.026
		Moderate	0.137	0.030	0.017	0.006	0.637	0.030
	Computer	Low	0.123	0.019	0.058	0.015	0.668	0.026
		Moderate	0.134	0.019	0.019	0.007	0.663	0.024
No preference ($n = 17$)	Human	Low	0.088	0.016	0.064	0.019	0.570	0.035
		Moderate	0.079	0.013	0.032	0.014	0.554	0.039
	Computer	Low	0.100	0.023	0.085	0.035	0.572	0.038
		Moderate	0.100	0.024	0.046	0.019	0.537	0.040

The analysis assessing anticipatory error correction (γ) revealed no significant main effect of Social Instruction, $F(1,41) = 1.69$, $p =.20$, $\eta_p^2 = .039$, but again a significant effect of VP Adaptivity, $F(1,41) = 13.92$, $p < .001$, $\eta_p^2 = .253$, with participants employing more anticipatory error correction during the low adaptivity condition than during the moderately adaptive condition. This means that there was a greater influence of the anticipated timing of pacing sequence over the planned timing of the next tap when the VP was less cooperative. There was no significant effect of Partner Preference, $F(2,41) = 2.41$, $p = .103$, $\eta_p^2 = .105$, but there was a significant three-way interaction between Social Instruction, VP Adaptivity and Partner Preference, $F(2,41) = 5.47$, $p = .008$, $\eta_p^2 = .211$ There were no other significant interactions, (all $p > .05$).

Similar to the accuracy results, the three-way interaction was analysed by conducting a series of dependent t-tests separately for each preference group, to compare anticipatory error correction at each level of VP adaptivity. For the human preference group, there was significantly less anticipatory error correction when drumming with the moderately adaptive partner during the computer instruction condition, $t(9) = 3.53$, $p = .006$, $d = 1.12$, but not when instructed that the partner was a human, $t(9) = -.51$, $p = .625$, $d = -.16$. Likewise, the computer preference group showed significantly less anticipatory error correction in the moderately adaptive partner condition, however, only with the human partner instruction, $t(16) = 2.88$, $p = .011$, $d = .70$, and not the computer partner instruction, $t(16) = .44$, $p = .67$, $d = .011$. Similar to the human preference group, the no preference group showed significantly less anticipatory error correction with the moderately adaptive partner during the computer instruction condition, $t(16) = 2.98$, $p = .009$, $d = .72$, but not with the human partner instruction $t(16) = 1.15$, $p = .266$, $d = .28$.

2.5 DISCUSSION

To investigate the effect of partner intentionality on interpersonal sensorimotor synchronisation and its underlying mechanisms, participants were asked to drum in time with either a computer or a human partner (an explicit social instruction relating to partner intentionality). In reality, participants were always drumming in time with a computer-controlled VP that simulated either a less adaptive or a moderately adaptive partner producing tempo-changing sequences (an implicit cue to partner intentionality). Overall, synchronisation performance improved (both synchronisation accuracy and stability) with the moderately adaptive VP, which was simulating a more responsive partner that implied an intention to coordinate; however, there was no direct effect of the explicit social instruction on synchronisation performance and its underlying mechanisms. Yet, once individual differences in partner preference were taken into account, effects emerged relating to the explicit social instruction, and these effects were dependent on the responsiveness of the VP.

There was a significant improvement in performance when the VP was more adaptive and implied an intentional partner. This suggests that when the VP was more adaptive and thus more responsive, participants modulated their performance in order to maximise the joint outcome. It appears that an implicit sense that a co-actor is actively contributing within a synchronisation task leads to adaptation of one’s own motor behaviour. This modulation in performance may occur because synchronisation with a more adaptive partner leads to a sense of a co-actor’s commitment and willingness to cooperate, resulting in more individual effort being applied to the joint task. Because we employed a within-subjects design, we can infer that an increase in VP responsiveness was interpreted as changes in intention to coordinate rather than a partner with a better ability to synchronise. However, further research into the way synchronisation behaviour is modulated when an individual takes into account both a partner’s intentions and their ability will be an important next step and may be investigated using the VP with a between-subjects design.

In contrast to the findings in regard to VP adaptivity, there was a lack of a direct influence of Social Instruction, which suggests that independent of explicit beliefs as to whom the interaction partner was (human or computer), performance was similar in terms of synchronisation accuracy and stability. Together, the results relating to the implicit cue of VP Adaptivity and the explicit Social Instruction demonstrate not only the importance of implicit behavioural cues during a joint task, but also the dissociation between implicit and explicit cues as to partner intentionality, and suggest that implicit cues could be more influential in the context of interpersonal synchronisation.

Although the explicit cue of partner intentionality had no direct effect on synchronisation performance, once individual differences for partner preference were considered, a more nuanced picture emerged for synchronisation accuracy. Depending on which apparent partner was preferred, there was an interaction between the implicit cue of VP adaptivity and the explicit Social Instruction. The accuracy results showed that for those who reported preferring to coordinate with one partner or the other, performance was significantly better when the VP was moderately adaptive, but only when instructed to drum with the partner that was congruent with their personal preference and not with the partner that was incongruent with this preference. This was despite the moderately adaptive condition being identical during both social instruction conditions. When these participants were told they were synchronising with their non-preferred partner, their performance did not improve with the moderately adaptive VP, even though the VP was correcting for a greater amount of asynchrony and an improvement was to be expected (see Fairhurst et al., 2013; Repp & Keller, 2008). This lack of improvement suggests that when synchronising with a partner who is not the preferred partner, individuals resist the aid of the more adaptive VP to the detriment of improved performance. It may be that a pre-existing belief or bias against a particular type of partner is triggered by the explicit instruction and can override the implicit sense of cooperativity, which would otherwise lead to improved joint performance.

Those individuals that reported no preference for either of the partner types showed similar improvements in performance with the more adaptive VP during both Social

Instruction conditions. The results relating to what we have labelled as ‘preference’ suggests that pre-existing ideas or stereotypes about how responsive or predictable a partner of a particular type is, may influence the way an individual approaches a joint synchronisation task. For instance, a general understanding of the way computers work may lead to an assumption that the computer will not be adaptive or responsive, and thus the perception may be that synchronisation will be more difficult. Alternatively, a computer may be perceived as more stable and predictable and thus easier to synchronise with. Likewise, a human partner may be thought to be more cooperative and therefore easier to synchronise with, or alternatively may be viewed as unstable and less predictable and may be judged to be more difficult to synchronise with. These findings extend existing evidence that top-down processes play a role in action co-representation during joint action (e.g. Brown & Brüne, 2012; Liepelt & Brass, 2010; Stenzel et al., 2012).

Indeed, the post hoc grouping of participants according to preferences is an exploratory factor, and definitive inferences cannot be drawn. Nevertheless, the pattern of results suggests that individual differences in personal preference for a synchronisation partner may modulate the interaction between explicit beliefs and implicit beliefs about a partner’s intention to coordinate during a sensorimotor synchronisation task. These results thus provide some initial evidence that individual differences in social attitudes may modulate performance during a joint action.

Concerning the mechanisms that underpin synchronisation, the implicit and explicit manipulation of intentionality had different effects on indices of each of the mechanisms (i.e., ADAM parameter estimates). Regarding period correction, there were no differences found between the conditions, indicating that individuals employed adaptive timing equally when synchronising, despite the apparent partner or the degree of adaptivity employed by the VP. In contrast, similar to the observed differences in synchronisation performance with the implicit cue of partner intentionality (VP Adaptivity), there were differences in the other underlying mechanisms of synchronisation performance—temporal anticipation and anticipatory error correction. Firstly, there was relatively more tracking behaviour (less anticipation), and secondly, less anticipatory error correction when the VP was moderately adaptive. In contrast to our predictions, this indicates that people reduce their effortful predictive processes when the synchronisation partner takes on more of the adaptive burden. In light of greater synchronisation accuracy and stability when the VP was moderately adaptive, these results suggest that participants may have put less effort into temporal anticipation when the partner evoked a greater sense of intentionality by being more cooperative.

Similarly, the lower anticipatory error correction estimates when the VP was more cooperative indicates that participants corrected for a smaller proportion of the difference between the output of the adaptation module (their estimate for self) and the anticipation module (their prediction of other). This suggests that when there is implicit information about co-actor intentionality, the contribution of the partner is recognised, and an individual may opt to rely more so on the more responsive partner to contribute to the joint performance in the form of social loafing (see Karau & Williams, 1993). Additionally, with the implicit sense of a responsive intentional partner, it may be assumed that the co-actor has the ability to take a follower role, which is not the case with an unintentional, unresponsive partner. Perhaps participants are more inclined to allow the balance of leading and following to shift between themselves and their partner when their partner is more responsive, requiring less active anticipation and anticipatory error correction. This may be tested in future experiments by explicitly instructing participants to lead or follow their partner while varying the adaptivity of the VP.

As with synchronisation performance, there was no direct effect of the explicit Social Instruction on the underlying mechanisms of synchronisation. However, similarly to the accuracy results, once individual subjective preferences were taken into account, the explicit social instruction was found to modulate the effect of VP adaptivity on anticipatory error correction. Specifically, when the VP was moderately adaptive compared to less adaptive, participants engaged in significantly less anticipatory error correction, but only during the Social Instruction that was incongruent with their preferred partner. This suggests that when the VP was more adaptive, participants were less likely to integrate their prediction of their partner's timing into their own planned next movement when instructed that they were synchronising with the non-preferred partner.

Given that the higher adaptivity and thus cooperativity of the VP was more likely to invoke a sense that the partner is 'like me' (Gallese, 2005) and is committed to achieving the joint goal to synchronise (Michael et al., 2016a, 2016b), more integration between self and other (reflected in larger anticipatory error correction estimates) was expected. However, perhaps those who preferred one partner to the other did not interpret the higher adaptivity as 'cooperative' or 'like me' when the explicit instruction led them to believe that the partner was not the preferred synchronisation partner. In this instance, rather than accepting the increased contribution of the partner as helpful, these participants may instead have inferred the higher adaptivity as being less stable and thus less predictable (also see Fairhurst et al., 2013) and therefore reduced the degree that their predictions of the partner's timing influenced their own subsequent movement timing.

Overall, the results of this experiment suggest that during synchronisation, implicit cues of partner intentionality are more influential than explicit cues. However, for some, explicit cues may take precedence when the implicit cues are incompatible with prior beliefs about how a particular partner should behave. This may resonate with Bayesian inference processes where the influence of priors becomes stronger when the available evidence is less reliable (Elliott et al., 2014; Ernst & Bülthoff, 2004). In our case, prior knowledge of how an intentional or an unintentional synchronisation partner behaves may influence beliefs about how responsive an interaction partner should be. These priors are activated by the explicit social instruction and then compared to the currently available evidence—the actual responsiveness of the partner (the degree of VP adaptivity). For those who may have stronger pre-existing expectations (or priors), the influence of the explicit instruction may be assigned greater weighting when the actual responsiveness of the VP is incompatible or contradictory to these priors. This could be further investigated by making the available evidence less reliable, for instance, increasing the variability of the VP by employing large degrees of adaptation that render the partner uncooperative (e.g., Fairhurst et al., 2013).

When interpreting the overall results of this study, the fact that participants had such different views as to which apparent partner was preferred is of itself noteworthy. Both conditions were identical, so it was expected that the majority of participants would find both conditions equally difficult. However, a majority of choices made were directional toward one ‘partner’ as being easier than the other. These differences in post-task subjective preference may have been driven by participants’ sensitivity to their performance being better in one condition over the other. However, based on the results of the current study, it is not possible to know what drove this preference choice. It may be that better synchronisation with the belief of a particular type of partner (human or computer) resulted in a preference for that partner OR a preference for a particular type of partner which led to better synchronisation with that partner. Either way, there was an effect of social instruction that differed depending on individual differences in partner preference. Which of these options is the explanation for the effect is still an open research question. This issue may be addressed in future research by a priori assessment of the type of interaction partner that is preferred (intentional or unintentional).

Nonetheless, of particular interest here is why, when the VP was more adaptive, the differences in accuracy and anticipatory error correction occurred depending on partner preference. It could be that pre-existing notions about which type of partner will be easier to work with, or a general preference for interacting with either an intentional or unintentional partner, may create a bias that then modulates the way one synchronises. Despite previous work showing that performance on a joint task differs depending on the belief of an intentional partner (e.g. Liepelt et al., 2010), this effect may be nullified when the responsiveness of the partner seems to be incompatible with pre-existing ideas about that partner's ability or competence. In this case, resistance to that partner's contribution may occur despite believed intentionality. For instance, those who preferred the computer partner may have perceived their apparent human partner as a more unpredictable partner and thus, when the VP was more adaptive, the increased variability was perceived as instability rather than a cooperative partner that is aiding with synchronisation.

In conclusion, the intentionality of a synchronisation partner does affect performance during an interpersonal sensorimotor synchronisation task; however, in general, implicit cues as to the intentionality of the partner appear to be more influential than explicit cues. This effect is also reflected in two of the underlying mechanisms of synchronisation, where people engage in less temporal anticipation and anticipatory error correction with a more adaptive partner. This indicates that people are more inclined to reduce the effortful allocation of resources when coordinating with a partner who behaves in a responsive manner. Secondly, individual differences in preference for synchronising with an intentional agent vs a static computer may interact with explicit instructions about who the interaction partner is. These differences were demonstrated for synchronisation accuracy and were further reflected within the underlying mechanism of anticipatory error correction, where it is proposed that the integration between self and other occurs (van der Steen & Keller, 2013). Taken together, this demonstrates that when investigating the role of partner intentionality on interpersonal behaviour, it is essential not only to consider characteristics of the interaction partner but also to take into account individual differences in social preferences or biases as potential modulating factors.

Chapter 3: The Role of Social Cues During Rhythmic Coordination: Sensorimotor Synchronisation with a Humanoid Robot.

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Note 1:
P.E. Keller is the first author’s primary supervisor.
C. J Stevens and G. Knoblich are on the first author’s supervisory panel
C. Stanton assisted with the experimental design and programming of the Nao robot
T. Macphearson assisted with data collection.

Note 2:
The International Journal of Social Robotics requires American English spelling, and so in this chapter, there will be some inconsistency with spelling compared to the other chapters in this thesis (e.g., synchronization instead of synchronisation).

Chapter 3: The Role of Social Cues During Rhythmic Coordination: Sensorimotor Synchronization with a Humanoid Robot

3.1 ABSTRACT

The influence of social interaction and engagement during coordinated movement is not fully understood. We investigated synchronized movement with either a partner that exhibited explicit communicative cues intended to encourage social engagement, or a static, non-engaging partner. The task was implemented with an embodied artificial agent, instantiated as an adaptive drumming humanoid robot that modulated the timing of its drum strokes in response to participants' drum timing. Participants (n = 33) drummed with 'SocialBot', a robot that used speech, eye gaze, and body movements to encourage social engagement, or 'MetroBot', a non-interactive robot that remained static except for the drumming movement. Both conditions included three levels of robot drumming adaptivity, ranging from minimally to moderately adaptive. We hypothesized that synchronization would improve with higher adaptivity and would be further enhanced with the interactive 'SocialBot'. As predicted, synchronization was more accurate when the robot was more adaptive. However, while SocialBot was rated more anthropomorphic, animate, and likable, the effect of robot interactivity depended on differences in post-task preferences. For those who found either of the robot interactivity conditions easier (despite identical objective difficulty), synchronization performance was unaffected by the version of the robot. However, those who found the two interactivity conditions equally difficult were more accurate with SocialBot. Additionally, those who preferred MetroBot had better synchronization performance, suggesting that synchronization ability may modulate subjective partner preferences. These findings suggest that explicit social cues affect performance independent of awareness, and that top-down processes modulate basic sensorimotor mechanisms during interpersonal coordination.

Keywords: sensorimotor synchronization, human-robot interaction, social interaction, joint action, virtual partner

3.2 INTRODUCTION

When people coordinate their movements with others to complete a joint task, such as musical group performance or working in a team, several sensorimotor and cognitive processes interact to enable successful interaction. To successfully coordinate, individuals interpret multiple explicit and implicit cues to predict what and when their partner's next action will occur and adapt their own movements within both space and time. Within this dynamic interaction, the joint nature of the task must be recognised; however, the extent to which individual characteristics of the interaction partner contribute to the development of a joint context and how this may, in turn, affect joint performance is unclear. For instance, do people modulate their own coordination processes based on whether their partner is perceived as intentional, engaged, and committed to achieving the mutual goal? Furthermore, what explicit and implicit social cues enhance this sense of mutual engagement, and do these facilitate coordination during a joint task?

When engaging in a task with another, establishing a 'joint context' heightens the feeling of 'we' are conducting this task together, rather than 'I' am performing this task alongside 'you'. A joint context can be established by individuals first engaging with each other to acknowledge the collaborative nature of the task, and continuous interaction and engagement can lead to a sense of joint agency—a 'we-agency' (Pacherie, 2014). The emergence of 'we-agency' can be influenced by the perceived nature of the co-actor in a joint action task, for example, whether the partner is perceived as an active agent who is committed, intends to coordinate, and will be responsive and adaptive during task performance, or alternatively, is a static agent, incapable of dynamic interaction. For instance, Obhi and Hall (2011a) found that a 'we-identity' was automatically formed when a task was performed with another person, however, when paired with a computer, this spontaneous 'we-identity' was not observed. With the increasing use of technology in everyday life and collaboration with computers and machines becoming the standard, it is essential to establish the specific conditions and cues necessary to develop such a sense of joint agency.

In human-human joint action, it is argued that co-representation—the ability to mentally represent not only one's own goals, intentions, and upcoming movements, but also the goals, intentions, and anticipated movements of a co-actor—is a necessary pre-requisite for successful coordination (Gilbert, 1992; Sebanz et al., 2003). The perceived intentionality of a co-actor is one factor that has been found to influence whether such co-representation occurs, with co-representation only occurring with co-actors that are portrayed as intentional agents (Atmaca et al., 2011; Tsai et al., 2008; Wohlschläger et al., 2003). However, Müller, Brass, et al. (2011) found that co-representation of unintentional, non-biological agents can occur if they are first attributed with intentional, life-like characteristics. Participants who viewed a "Pinocchio" animation that portrayed a wooden puppet behaving intentionally showed evidence of co-representation when completing a joint task with a wooden hand, as opposed to participants who had not viewed the animation. Thus, the intentionality attributed to an interaction partner—otherwise known as 'the intentional stance'—modulates the processes underlying interpersonal interaction during a joint task (Dennett, 1987; Thellman et al., 2017).

Another critical aspect that facilitates joint action is a sense of commitment between human actors that each will contribute their part to achieve the joint goal. This mutual commitment between two or more people may be generated through the open expression of each co-actors personal readiness to behave cooperatively to realize a shared intention or goal (Gilbert, 1992). This sense of commitment allows one to expect the contribution of other agents when pursuing joint goals, which then facilitates cooperation and coordination (Michael et al., 2016a; Michael & Pacherie, 2015).

Such findings related to the role of partner intentionality and commitment during joint performance, highlight that higher-level contextual knowledge—such as explicit and implicit beliefs about a partner and their intentions—interact with lower-level automatic perceptual processes that are used to coordinate movement with others. To examine this, we investigated the effect of partner intentionality on the mechanisms underpinning real-time interpersonal coordination to further understand how implicit and explicit cues relating to the intentionality of a co-actor affect performance during a sensorimotor synchronization task (Mills et al., 2019). We simulated a social context during a series of drumming tasks and instructed pairs of participants that they were synchronising with either a computer or an intentional human partner (an explicit cue of partner intentionality). In reality, participants were always drumming with a virtual partner (VP)—an adaptive auditory pacing sequence that was set to various levels of adaptivity, thus simulating a more or less responsive partner (an implicit cue as to the intentionality of the partner) (Fairhurst et al., 2013; Repp & Keller, 2008).

The results showed that synchronization accuracy was generally improved when the VP was more adaptive and implicitly portrayed an intentional, responsive partner. However, this was modulated by the explicit social instruction about who the synchronization partner was and was also affected by individuals' post-task subjective judgements about which partner was easier to synchronize with. For some, performance improved with the more adaptive VP, however, only when told that they were drumming with their preferred partner, but not with the alternative partner. For instance, those who judged the computer partner as easier to synchronize with, improved with the more adaptive VP, only when told they were synchronising with the computer but not with the human partner. These results show that implicit cues as to the intentionality of a partner influence synchronization performance, however, this influence is modulated by explicit beliefs about intentionality and is also affected by individuals' biases or personal preferences for interacting with people or computers.

A strategy that may be used to examine further the effect of partner intentionality and commitment—and the role of implicit and explicit cues of intentionality and commitment—is to use non-human agents, such as robots, as the interaction partner (Clodic et al., 2017; Michael & Salice, 2017; Urgen et al., 2013). Due to their precise programmable behaviours, robots afford tight experimental control while still allowing a tangible interactive partner, generating a pseudo-naturalistic social context. For example, partner intentionality has been investigated using a humanoid robot by Stenzel et al. (2012), who found that during a joint task, co-representation of a robot partner only occurred when the robot was portrayed to function in a biologically inspired 'human-like' way, compared to a deterministic machine-like manner. This finding provides further evidence that the intentional stance of the interaction partner plays an important role during joint action, even when the partner is not an active agent.

Whether or not a robot can be viewed as intentional and committed depends upon whether the robot is considered a social being. Thus, the field of social robotics has been using human communicative techniques to enhance human-robot interaction. By incorporating design strategies that explicitly emulate human communication, robots can become anthropomorphized, leading to the attribution of agentic traits, such as intentionality and commitment, to an embodied virtual agent or a robot (Hortensius & Cross, 2018; Wiese et al., 2017). It has been demonstrated that more anthropomorphic machines are more likely to prime imitation (Castiello et al., 2002) and be emulated by human co-actors (Kory Westlund et al., 2017), providing evidence that anthropomorphized robots are more likely to be treated as active, engaged co-agents, facilitating the formation of a joint agency.

In addition to explicit communicative techniques, robot anthropomorphism may be influenced by more implicit cues such as how responsive or adaptive the robot partner is. During human-human coordination, an understanding that the other actor is ‘like-me’ and will mutually employ a similar set of skills reciprocally and adaptively aids coordination performance (Gallese, 2005). However, when the other agent is a machine or a robot, one cannot make such an assumption. To address this, virtual partners that are adaptive and dynamically respond to a human partner in real-time have been developed (Dumas et al., 2018; Kelso et al., 2009; Repp & Keller, 2008). Combining the responsiveness of an adaptive virtual partner with explicit social cues displayed by an anthropomorphic robot may encourage a sense of mutual cooperation, which in turn may lead to increased feelings of joint commitment and joint agency (Breazeal et al., 2016; Dumas et al., 2018; Gratch et al., 2007; Kelso et al., 2009; Stevens et al., 2016). Accordingly, the combination of explicit social-communicative signals and implicit behavioural cues may contribute to a sense that a co-actor is a committed and intentional agent during interpersonal interaction.

Explicit social cues may include communicative behaviours such as body language, eye gaze, and verbal interaction. These cues aid in establishing a joint context by explicitly demonstrating that a co-actor is actively engaged and is committed to cooperating to successfully complete a given task. Body language is commonly used to communicate during musical ensemble performance. For instance, head-nodding can indicate intended timing (Badino et al., 2014; Bishop & Goebl, 2018), while mutual eye gaze can communicate joint attention and intention to coordinate (Khoramshahi et al., 2016; Stanton & Stevens, 2014, 2017; Tomasello & Carpenter, 2007). Additionally, verbal interaction between co-performers provides a direct method to articulate an intention to coordinate and provide ongoing evaluation throughout the progression of the task. Such communication can build rapport between co-actors by not only establishing the joint context but also making explicit the commitment to cooperate during the joint task. By verbally reiterating and reaffirming the joint nature throughout the completion of the task (e.g., providing positive feedback about how the collective performance is progressing), rapport can be maintained, facilitating an ongoing sense of joint agency (Castro-Gonzalez et al., 2016).

Correspondingly, implicit behavioural cues may also elicit a sense of joint agency by subtly communicating that the co-actor is a responsive and interactive partner. For example, in our previous study (Mills et al., 2019), synchronization performance was improved with the more responsive and adaptive virtual partner. The relevance of partner responsiveness during human-machine interaction has also been demonstrated by incorporating various levels of contingency during non-verbal virtual agent responses. Feelings of rapport increased when humans were partnered with a contingently responsive virtual agent listener (Gratch et al., 2007), and children were more likely to seek information from a robot co-actor when the robot displayed contingent nonverbal communicative cues (as opposed to random cues) (Breazeal et al., 2016). These results demonstrate that implicit functional cues show that a robot co-actor is responsive, interactive, and adaptive, which may facilitate the formation of a joint context.

It is important to note, however, that the impact of explicit and implicit cues as to the intentionality of a co-actor may be moderated by individual differences in partner preference and task expertise. For example, individuals who prefer interacting with machines or those with social deficits may not necessarily perform better with an interactive and engaged co-actor (Bird et al., 2007). Additionally, as previously mentioned, in our study (Mills et al., 2019), individual's post-task perceptions of task difficulty with different types of interaction partners modulated the degree to which implicit cues interacted with explicit instructions to influence synchronization performance. Specifically, after a drumming task with the belief of either a human or computer partner, participants who judged that it was easier to synchronize with one partner over the other showed improved drumming performance with the more adaptive VP only when synchronising with the partner they perceived as the easier partner. In other words, participants resisted the aid of the more adaptive VP to improve performance when drumming with the apparent partner that was incongruent with their preference. These results indicate that individual differences in preferences may interact with the effect of different partner types. However, what was unclear from our previous study was whether pre-existing preferences or biases drove the modulation in performance, or if performance in the task drove the reported preference.

3.2.1 The present study

The current study aimed to investigate how both explicit signals that imply social engagement and implicit cues that suggest a responsive and adaptive partner affect performance during interpersonal rhythmic coordination when the partner's agency is not in question. We also aimed to further investigate the role of individual differences in preferences for coordinating with more or less interactive partners during joint synchronization. To this end, we used an Aldebaran Nao humanoid robot as a rhythmic synchronization partner in a joint drumming task that required the participant and the robot to produce auditory sequences together. To capture real-world joint performance demands, the sequences contained tempo changes resembling the slowing down and speeding up found in expressive musical performance (Colley, Keller, et al., 2018; Pecenka & Keller, 2011).

To investigate the effect of explicit cues indicating social engagement, participants drummed with the robot under two different interactive conditions. These conditions were described as two different versions of interactive software that were run separately on the same robot. One version of the software, referred to as ‘SocialBot’, implemented speech, eye gaze, and body movements to encourage social engagement, while the other— ‘MetroBot’ (short for ‘MetronomeBot’), was non-interactive and remained static except for the drumming movement. The cues exhibited by the SocialBot version, which involved verbal interaction, social eye gaze, and head nodding to indicate the beat, were designed to convey the robot's intention to temporally coordinate and their commitment to the task. As an implicit cue to the interactivity of the robot, a VP algorithm was employed to implement varying degrees of adaptivity (i.e., the proportion of each asynchrony that was compensated for by an error-correction routine), implying various degrees of partner responsiveness (Fairhurst et al., 2013; Repp & Keller, 2008). To extend the findings of Mills et al. (2019), in addition to the low and moderate adaptivity conditions, a third, high adaptivity condition was included to test whether a highly responsive partner further influences the effect of implicit social cues on synchronisation performance.

The role of individual differences in personal preference for different types of partners was also investigated. As in Mills et al. (2019), participants' post-task subjective ratings of task difficulty and evaluations of the two versions of the robot were assessed. In the context of the synchronization task, it was assumed that the condition participants deemed the easiest would reflect the condition they preferred. Based on this, we operationally defined this subjective judgement as 'Post-task Robot Preference' within this paper. We additionally sought to explore to what extent pre-existing preferences versus preferences that are developed during the experience of the task contribute to differences in performance with the two versions of the robot. To assess this, in addition to the post-task evaluations of the robot versions, prior to the task, we collected participant preferences for working with either a human or a computer.

To examine the effects of explicit and implicit social cues on sensorimotor and cognitive processes that regulate the dynamics of rhythmic interpersonal coordination, we assessed synchronization performance (accuracy and precision), as well as estimates of the underlying mechanisms that facilitate coordination. These mechanisms include temporal adaptation and anticipation, and the link between these two mechanisms via anticipatory error correction. Adaptation is a retrospective process that corrects previous synchronization errors, while anticipation involves the prediction of a future event produced by a co-actor. Anticipatory error correction integrates these adaptive and anticipatory processes, enabling correction of potential future timing errors before they occur. Using a computational model (developed by van der Steen, Jacoby et al., 2015; van der Steen & Keller, 2013) referred to as 'the ADaptation and Anticipation Model (ADAM)', we used synchronization data to generate estimates of each of these underlying processes in order to better understand how they each vary as a function of partner social engagement and adaptivity.

We expected that the interactive robot that used explicit human social communicative cues would be rated as more animate, anthropomorphic, and likable than the non-interactive robot. Therefore, SocialBot would be perceived as a more intentional and committed interaction partner than MetroBot, facilitating a stronger sense of joint agency, which we hypothesized, would lead to better synchronization with SocialBot. We also hypothesized that synchronization performance would be improved with higher degrees of robot drumming adaptivity, and we furthermore predicted that the combination of both explicit social cues and higher degrees of robot responsiveness (VP adaptivity) would lead to even greater improvements in performance. In addition, based on Mills et al. (Mills et al., 2019), we predicted that there would be relatively less temporal anticipation and less anticipatory error correction in the higher adaptivity conditions, reflecting efficiency in effortful processing when the partner is implicitly more responsive and taking on more of the synchronization burden.

In regards to individual differences in preference for partner type, following the results of our previous study (Mills et al., 2019), we predicted that any improvements in drumming would be consistent with individual differences in post-task preferences for either of the versions of the robot. Specifically, we predicted that subjective judgements about the robot that is easiest to synchronize with would interact with the effect of adaptivity and robot social engagement, such that improvement in drumming performance in the higher adaptivity condition may only occur when participants are synchronising with the robot version they perceive as easiest to synchronize with. Whether pre-existing preferences for human versus computer interaction would emerge to be a contributing factor was an open question.

3.3 METHOD

3.3.1 Participants

The participants were 33 adults (7 Male; *M*age = 23.7years, *SD* = 6.97) who were either from Western Sydney University and participated for course credit in a first-year university psychology course or were volunteers from the local community who responded to an advertisement and received a small travel reimbursement of $20. Fourteen participants reported having >2 years of musical experience (*M* = 10.57 years, *SD* = 6.66), and all participants reported normal hearing. After excluding three participants who did not record sufficient drumming data (see data analysis), 30 participants remained in the sample. The experiment was approved by Western Sydney University's research ethics committee, and all participants provided informed written consent prior to participation.

3.3.2 Design

The experiment used a (2 x 3) x 3 mixed design, with two repeated-measures variables and one between-subjects variable. The first repeated-measures variable was the interactivity of the robot, with two levels: the interactive version of the software 'SocialBot' or the non-interactive version 'MetroBot'. The second repeated-measures variable was the degree of adaptivity of the adaptive pacing sequence with three levels, including low adaptivity, moderate adaptivity, and high adaptivity. The third variable was between-subjects and based on participants’ post-task subjective preference for which robot interactivity condition was easiest. As in our previous study (Mills et al., 2019), participants were divided into three groups depending on whether they reported it easier to synchronize with the interactive robot, ‘SocialBot’, the non-interactive robot, ‘MetroBot’, or if they found that both versions of the robot were the same. The dependent measures comprised of behavioural measures of synchronization accuracy (mean absolute asynchrony) and precision (SD of asynchrony); as well as model-based estimates of each participant’s use of temporal adaptation (reactive error correction), anticipation (tempo change prediction), and anticipatory error correction (the degree to which upcoming movement timing is adjusted based on the comparison of adaptation and anticipation estimates; see Data Analysis).

In addition, the contribution of both pre-task and post-task preferences to the differences in accuracy between the two robot versions was assessed. Pre-task and post-task preference measures were assessed as predictors of the difference between drumming accuracy with SocialBot compared to MetroBot (collapsed across adaptivity levels).

3.3.3 Materials and Stimuli

Participants used a wooden drumstick with a nylon tip to drum on a Yamaha DTX TP70S drum pad, which was held on a metal drum stand in front of the participant. The drum pad was connected to Roland TD-9 Percussion Sound Modules, which were attached to Motu Microlite MIDI interfaces. These were, in turn, connected to an Acer laptop running Windows software. A custom-made C++ program recorded the tapping data as well as presented the auditory stimuli, which were presented through Sennheiser HD650 headphones connected to the laptop. End-to-end latency measures taken before the experiment revealed a mean delay of 60ms (*SD* = .9ms), which was accounted for by the program.

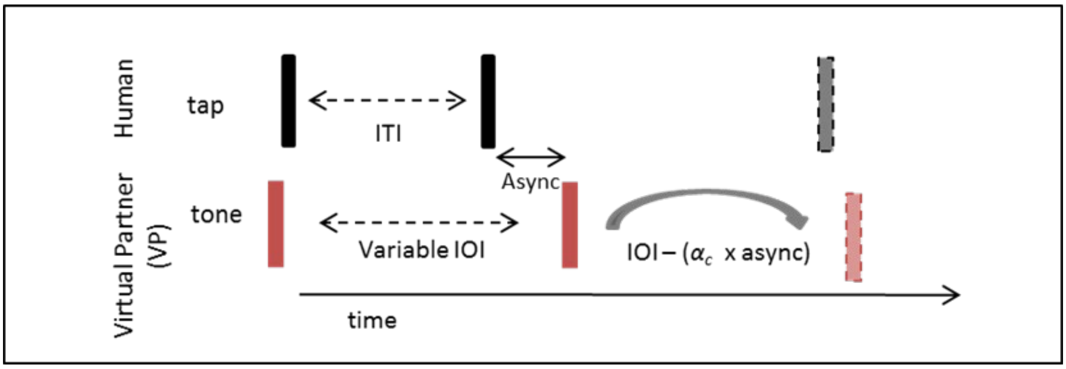
The stimuli were auditory sequences of percussion sounds. Each sequence started with four synthesized cowbell tones, followed by 60 synthesized woodblock tones with clear onset and decay. A beep indicated the end of the trial. The sequences progressed through tempo variations that accelerated and decelerated following a sinusoidal function (Colley, Keller, et al., 2018; Mills et al., 2015; Pecenka et al., 2013; Pecenka & Keller, 2011). These sequences varied between 500 and 600ms, with step sizes ranging between 1 and 32ms. This pattern of variation in the sequences was chosen to reflect tempo changes that resemble those observed during expressive timing in musical performance and were realistic patterns that could be produced by a non-expert participant.

In addition to these tempo variations, the adaptive function of the virtual partner was applied to implement a correction that adjusted the phase relation between drumming movements of the robot and the human participant (see Figure 3.1). This adaptive function simulates human phase error correction by correcting the timing of the subsequent sound by a proportion of the asynchrony between the last tone and the corresponding tap (Repp & Keller, 2008). Three levels of adaptivity were used, .1, .4, and .7, with each value representing the proportion of the asynchrony between the tone and the drum tap in the previous event that was corrected for in the subsequent event. A linear phase correction model based on Vorberg and Schulze (Vorberg & Schulze, 2002) controlled this process with the algorithm:

$$t_{n+1} = t_n + T + a_c \times async,$$

where t_n = time of pacing event, T = base Inter-Onset Interval (IOI; drawn from the tempo changing sequence), a_c = phase correction parameter implemented by the computer (.1, .4, or .7), and $async$ = asynchrony between tap and pacing event. For example, if a participant tapped too early (a negative asynchrony) to the previous tone, the subsequent event would occur earlier by a proportion (.1, .4, or .7) of that asynchrony. Thus, each IOI throughout the tempo changing sequence was adjusted in response to the amount and direction of the last tap's asynchrony.

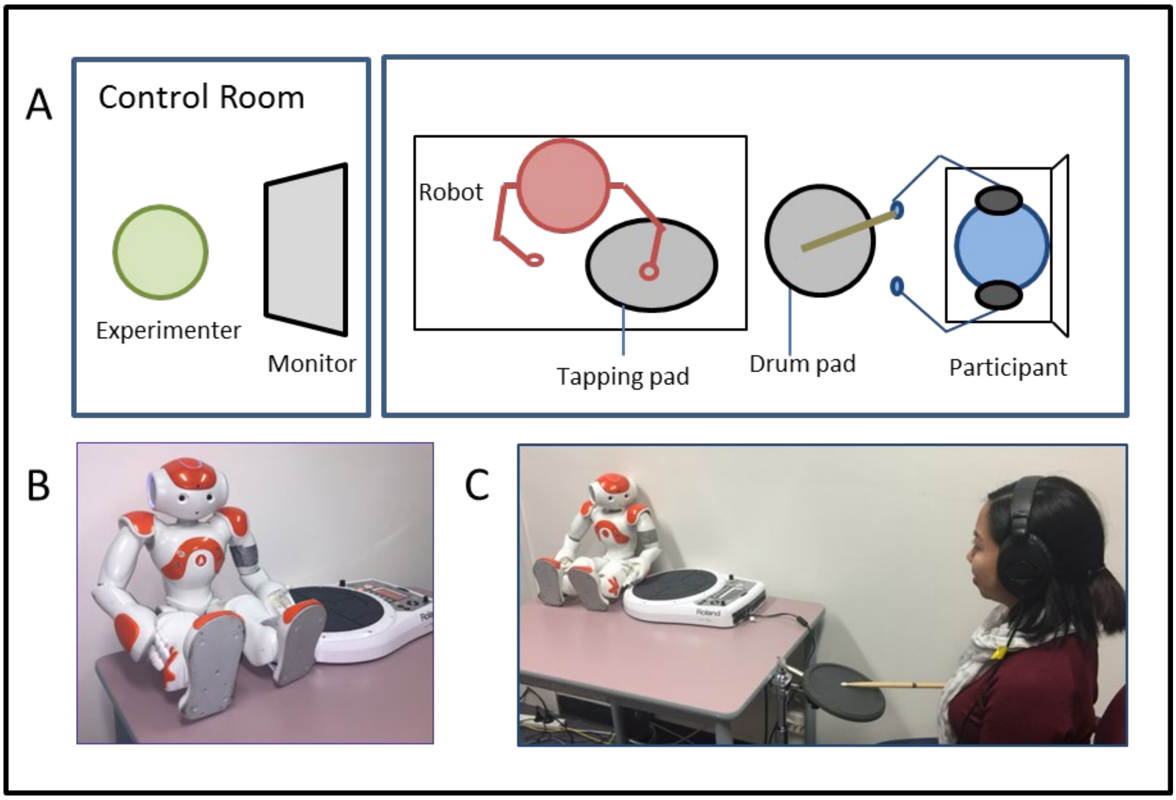
Figure 3.1: The adaptive timing mechanism of the virtual partner.



Note: A Graphical description of the virtual partner algorithm that controlled the timing of the auditory sequences and the robot drumming movements. Phase correction alters the timing of the subsequent inter-onset interval (IOI) by adjusting for a proportion (α_c) of the asynchrony (async.) between the last pacing event and the corresponding drum tap.

A single Aldebaran Nao, a small humanoid robot, was used as the drumming partner (See Figure 3.2B). The robot was seated on a table adjacent to the drum pad so that the participant faced the left side of the robot facing the drumming arm (Figure 3.2C). The robot was programmed to make a downward movement of the left arm so that the back of the robot's hand tapped on a Roland Handsonic 10 percussion pad. These movements were programmed to be simultaneous to the delivery of the auditory stimuli so that there was an illusion that the robot was generating the sounds by tapping on the percussion pad. The robot spoke using the Nao's default text-to-speech settings using a genderless robotic voice with expressive intonation.

Figure 3.2: The experimental setup.



Note: (A) Schematic of the experimental Wizard-of-Oz setup. The robot sat on a table facing away from the participant, while the participant sat behind a drum-pad placed perpendicular to the robot. The robot ‘drummed’ on a tapping pad using the left arm. A second experimenter viewed a live feed of the experiment from an adjacent control room and initiated the communicative behaviours of the robot. (B) The Nao humanoid robot as ‘MetroBot’. MetroBot faced away from the participant and, except for the drumming motion, remained static throughout all trials. (C) As ‘SocialBot’, the robot head turned toward the participant before and during each drumming trial.

Unknown to the participant, a ‘Wizard of Oz’ setup was used to control the interactions of the robot. This involved a second experimenter in an adjacent room viewing and listening to the experiment in real-time through a monitor, which was connected to a video camera and microphone placed in the room with the participant (Figure 3.2A). The robot was connected via an Ethernet cable to a modem that connected to both the laptop running the stimuli software as well as a separate laptop which was used to control the robot's interactive movements.

To assess the participant's perception of the two versions of the robot, The Godspeed Questionnaire (Bartneck et al., 2009) was completed. This questionnaire has been widely used in social robotics and contains five subscales: *Anthropomorphism, Animacy, Likeability, Perceived Intelligence and Perceived Safety.* Each subscale includes five items that each contain a 5- point semantic differential scale. The scores of the five items are then averaged to form an overall score for each subscale. For the purposes of the current study, the scores on the anthropomorphism, animacy, and likeability scales were of interest. Example items include "machine-like vs human-like" (anthropomorphism), "mechanical vs organic" (animacy), and "friendly vs unfriendly" (likeability).

3.3.4 Procedure

Participants were seated behind a drum, facing the robot's left-hand side, so the left drumming arm of the robot was completely visible (Figure 3.2C). After providing consent, participants completed a brief demographic questionnaire that included the rating of pre-task partner preference, which was indicated by ratings on a 7-point Likert scale to the question "I prefer working with…" with 1 indicating a human and 7 indicating a computer. Participants were then told a cover story that explained that the overall goal was to develop an interactive drumming robot that could synchronize its drumming with human partners, and the aim of the current experiment was to test and evaluate two different versions of the robot drumming software. The experimenter explained that one version of the software titled 'MetroBot' (short for MetronomeBot) was similar to a calculator and would try to synchronize by using a mathematical algorithm. The other version of the software titled 'SocialBot' was designed to be interactive and would use similar mechanisms as a human in order to synchronize. The participants were informed that their task was to drum in time with both versions of the drumming software in order to provide an evaluation of each program at the end of the experiment.

Participants completed two practice blocks containing three practice trials, with both versions of the software, always starting with SocialBot. The experiment then consisted of four blocks, each containing 12 trials; two of these were SocialBot blocks, and two were MetroBot blocks, which was indicated to the participant by a sign placed behind the robot. Within each block, there were four trials of each level of adaptivity ($a_c \ = .1$, .4, or .7) which were delivered in either ascending or descending order. The four blocks were given in a counterbalanced order, alternating between the SocialBot and MetroBot conditions.

At the beginning of each block, the experimenter would pretend to load either of the programs onto the robot by pressing a touch-screen controller, at which point the robot verbally said, “software loaded” (in reality, this was always controlled by the second experimenter in the adjacent room using the Nao’s inbuilt text-to-speech function). The pre-trial behaviour differed between the two robot versions. Before the initial SocialBot practice trials, SocialBot would turn and introduce itself to the participant. ‘SocialBot’ (controlled by the second experimenter) would look around the room moving its gaze between the experimenter and the participant while the experimenter provided instructions and would then turn its head to the participant and say, “Hi, I’m Nao, what is your name?” When the participant replied, SocialBot would reply, “Nice to meet you <participant name>, I think we will have fun together”. There was no such interaction at the beginning of the MetroBot trials, with the robot remaining completely static, with the robot’s gaze facing away from the participant.

The robot behaviour also differed between the two robot versions throughout the drumming trials. At the beginning of each individual SocialBot trial, the robot would turn its head to look at the participant, nod in time to the four lead-in-tones, and then move its gaze toward the participant's drum as though 'watching' the drumming actions of the participant. SocialBot was also programmed with various encouraging sayings such as "Let's do this" and "That was awesome", which it randomly stated either before or after 50% of trials. During the MetroBot trials, the only movement of the robot was the drumming arm, and the robot did not engage in any verbal behaviour. MetroBot never gazed at the participant, with its head always looking straight ahead, at a 90-degree angle away from the participant.

After the drumming blocks were complete, the participants completed the GodSpeed questionnaire and an evaluation of the two drumming programs, including the question "Which version of the program was easier to synchronize with?" with three forced-choice response options of "SocialBot", "MetroBot", and "It was the same"

3.3.5 Data Analysis

Pre-processing of data and screening for missing taps or taps with a large asynchrony (defined as an asynchrony of more than ± the current IOI) was conducted using MATLAB. Linear interpolation was used to correct for any missing taps or taps with a large asynchrony; however, any trials that contained more than three such problem taps were excluded from the analysis. Participants who had four or more trials excluded out of the eight trials in each condition for any of the above reasons were removed from the analysis. Three participants did not meet this criterion and were subsequently removed.

A (2 x 2) x 3Analysis of Variance (ANOVA) was conducted on each of the dependent measures measuring synchronization performance (synchronization accuracy and precision) and the underlying mechanisms of synchronization (temporal adaptation, anticipation and anticipatory error correction). All effects are reported as statistically significant at $p < .05$. Synchronisation accuracy (mean absolute asynchrony—calculated by subtracting the onset time of the current tap produced by the participant from the onset time of the current tone generated by the VP program), and precision (SD of asynchrony). These measures (mean absolute asynchrony and SD asynchrony) were calculated for each trial and then averaged across all trials within each experimental condition.

Parameter estimates of temporal adaptation, anticipation, and anticipatory error correction were calculated using ADAM for each trial separately (see van der Steen, Jacoby, et al., 2015). The so-called Joint ADAM Beta version of the model was employed, where the adaptation module includes a parameter for period correction, which is an intentional response to a perceived tempo change that adjusts the rate of the internal timekeeper. Model estimates of period correction are calculated based on a linear autoregressive error correction model and represent the degree to which one adjusts the period of the internal timekeeper by a proportion of the most recent asynchrony. The anticipation module contains a parameter for temporal anticipation, which is instantiated as the weighted sum of both predictive (linear extrapolation based on the previous two inter-onset intervals) and tracking processes (where the previous inter-onset interval is copied and repeated). An anticipation estimate of .5 represents that equal prediction and tracking is occurring, whereas values greater than .5 represent relatively more prediction than tracking and values less than .5 represents relatively more tracking.

The parameter for anticipatory error correction is computed by a joint module that compares the output of the adaptation module (timing of next planned movement) to the output of the anticipatory module (prediction of others next produced sound) and corrects for a proportion of the difference between the two. The result is that a predicted asynchrony between a tap and a tone may be corrected before it occurs. When the anticipatory error correction value is closer to 0, the next movement is driven more so by the output of the adaptation model (one’s own motor plan). Whereas as this parameter becomes closer to 1, the output of the anticipation module (prediction of other’s sound) is increasingly incorporated into the timing of the next movement (the more influence the prediction of the other’s timing has over the planned timing of the next movement) (van der Steen, Jacoby, et al., 2015).

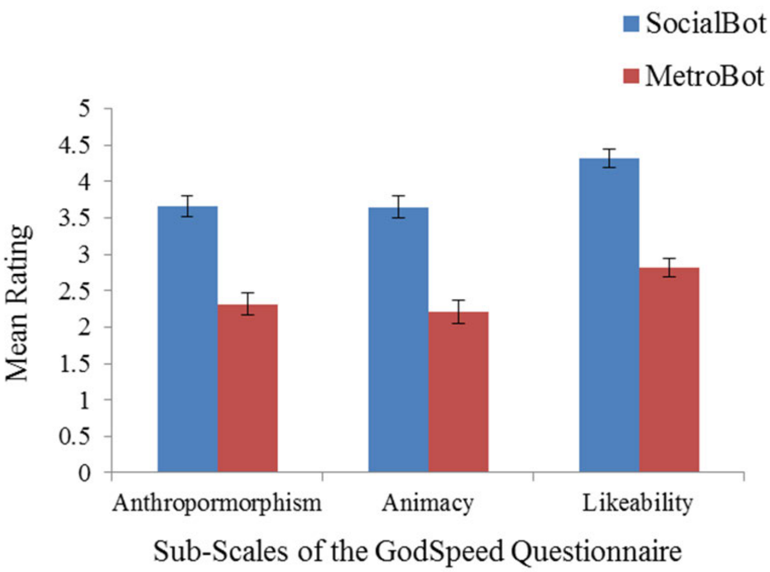
The procedure for calculating parameter estimates for each trial per participant entailed fitting ADAM to the empirical behavioural data from each trial using a bounded Generalized Least Squares method (see Jacoby et al., 2015; van der Steen et al., 2015). For each participant, these parameter estimates were then averaged across corresponding trials within each condition. Prior to averaging, a log transformation was applied to both absolute asynchrony and the period correction estimates in each of the six conditions to correct for violations of normality.

To assess differences in post-task preferences for synchronising with either robot, participants were divided into groups based on their response to the question, “Which version of the program was easier to synchronize with?” As in Mills et al. (2019), this grouping was used as a between-subjects factor in the ANOVA, with the categorization of three groups including the “SocialBot preference group” ($N = 11$), the “MetroBot preference group” ($N = 9$), and the “No preference group” ($N = 10$). In addition, a secondary regression analysis was conducted to assess the extent that pre-existing preferences versus post-task preferences contribute to differences in performance between the two versions of the robot. To indicate this difference in drumming performance between SocialBot and MetroBot, a difference score was calculated by collapsing the accuracy data across the different levels of adaptivity and subtracting the data obtained during the MetroBot condition from the data obtained during the SocialBot condition.

3.4 RESULTS

The subjective evaluations of the two versions of the robot were firstly assessed to confirm that the interactive robot was judged as more human-like. The responses to three of the subscales of The GodSpeed questionnaire were analysed using a series of paired sample t-tests which compared the mean ratings for each robot in the areas of *Anthropomorphism,* *Animacy, and Likeability* (Figure 3.3). As hypothesized, SocialBot was rated significantly more anthropomorphic ($M = 3.66$, $SD = .76$) than MetroBot ($M = 2.31$, $SD = .83$) $t(29) = 5.72$, $p < .001$, with large effect size indicated by $M_{\text{diff}} = 1.35$, $r^2 = .53$, 95% CI = .87-1.83. Likewise SocialBot was rated as more animate ($M = 3.65$, $SD = .83$) than MetroBot ($M = 2.2$, $SD = .84$), $t(29) = 6.34$, $p < .001$, (large effect size indicated by $M_{\text{diff}} = 1.44$, $r^2 = .58$, 95% CI = .98-1.90), and also more likable ($M = 4.31$, $SD = .71$) than MetroBot ($M = 2.82$, $SD = .71$), $t(29) = 6.89$, $p < .001$, (large effect size indicated by $M_{\text{diff}} = 1.49$, $r^2 = .62$, 95% CI = 1.04-1.94).

Figure 3.3. Mean Ratings of the Two Robot Versions.



Note: Mean ratings out of 5 for the subscales of *Anthropomorphism, Animacy,* and *Likeability* from the GodSpeed Questionnaire for both SocialBot and MetroBot. Error bars represent standard errors of the mean.

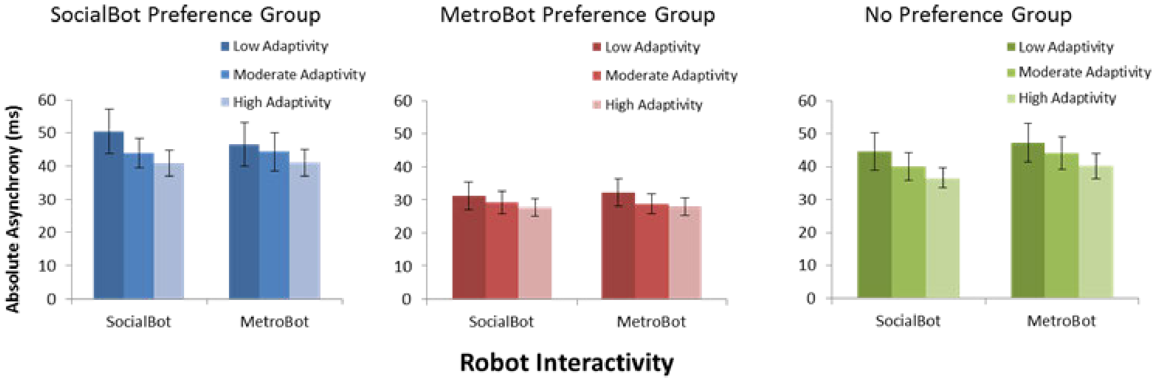
To assess the effect of robot interactivity, adaptivity, and the effect of post-task preferences, a mixed (2 x 3) x 3 ANOVA was conducted, with the two repeated measures factors of Robot Interactivity (SocialBot vs MetroBot) x VP Adaptivity (Low, Moderate, or High) and one between groups measure of Post-task Robot Preference (SocialBot Easier, MetroBot Easier, No Preference) on each of the dependent measures: mean absolute asynchrony, SD asynchrony, temporal adaptation (period correction), anticipation, and anticipatory error correction estimates. Prior to these analyses, a preliminary ANOVA of all measures confirmed there were no effects of condition order and no relationship between the presentation order of conditions and the post-task subjective preference indicating which condition was easiest. Assumptions of sphericity and homogeneity of variance were met.

3.4.1 Synchronisation Performance

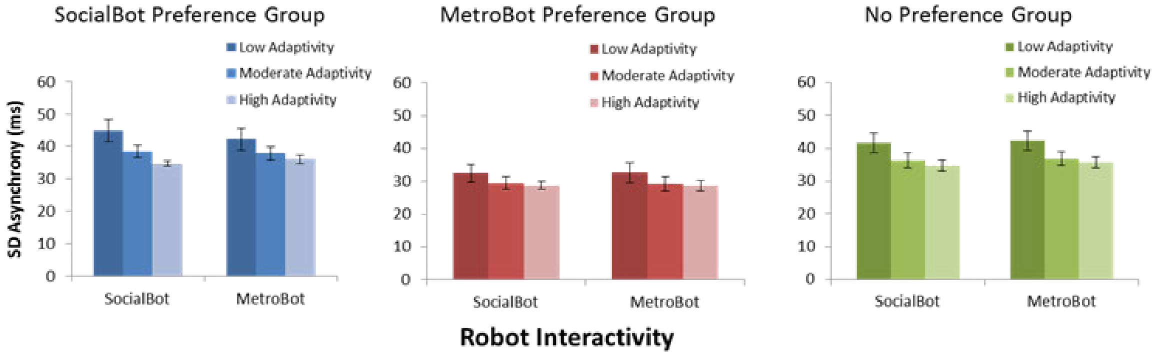
Synchronisation performance was assessed in terms of synchronization accuracy (mean absolute asynchrony) and synchronization precision (SD of asynchronies) for each preference group and can be seen in Figure 3.4. The ANOVA on log-transformed absolute asynchrony revealed a significant main effect of VP Adaptivity $F(2,54) = 23.15$, $p <.001$, $\eta_p^2 =.462$ (Figure 3.4A). As hypothesized, there was significantly lower asynchrony (more accuracy) in the high adaptivity condition than both the moderately adaptive condition and the low adaptivity condition; and the moderately adaptive condition also showed significantly less asynchrony than the low adaptivity condition. In addition, there was also a main effect of preference group $F(1,27) = 3.89$, $p = .03$, $\eta_p^2 =.224$ with the group that found it easiest with MetroBot being significantly more accurate than either the SocialBot preference group, or those who found it the same. There was no main effect of Robot Interactivity, but there was a significant 2-way interaction between Robot Interactivity and Post-task Preference group $F(2,27) = 4.58$, $p = .019$, $\eta_p^2 =.25$.

Figure 3.4: Measures of synchronization performance.

A. Accuracy



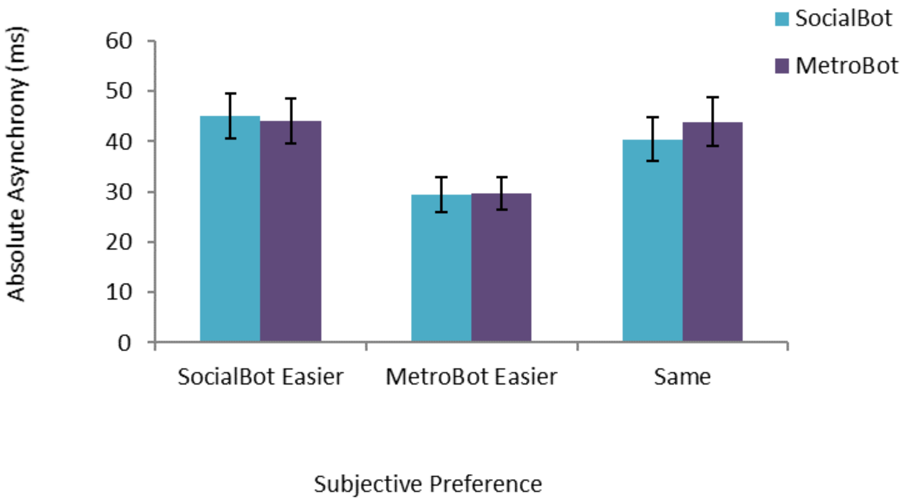
B. Precision



Note: Mean synchronisation accuracy and precision for the three preference groups based on post-task subjective judgement of task difficulty, split between the interactive robot condition (SocialBot) and the non-interactive robot condition (MetroBot). (A) – Accuracy (Mean Absolute Asynchrony, untransformed). (B) - Precision (SD Asynchrony). Error bars represent standard errors of the mean.

This interaction was analysed by collapsing data across adaptivity levels and conducting paired sample *t*-tests comparing the two robot versions separately for each Post-task Preference group (Figure 3.5). There was no difference detected between the robot interactivity versions in synchronization accuracy for the MetroBot preference group or the SocialBot preference group; however, there was a significant effect for the group that reported that both versions were equally as easy to synchronize with *t*(9)= -2.739, *p* = .003 with accuracy for this group being higher when drumming with SocialBot than with MetroBot.

Figure 3.5: The Interaction Between Robot Interactivity and the Preference Groups for Synchronization Accuracy.



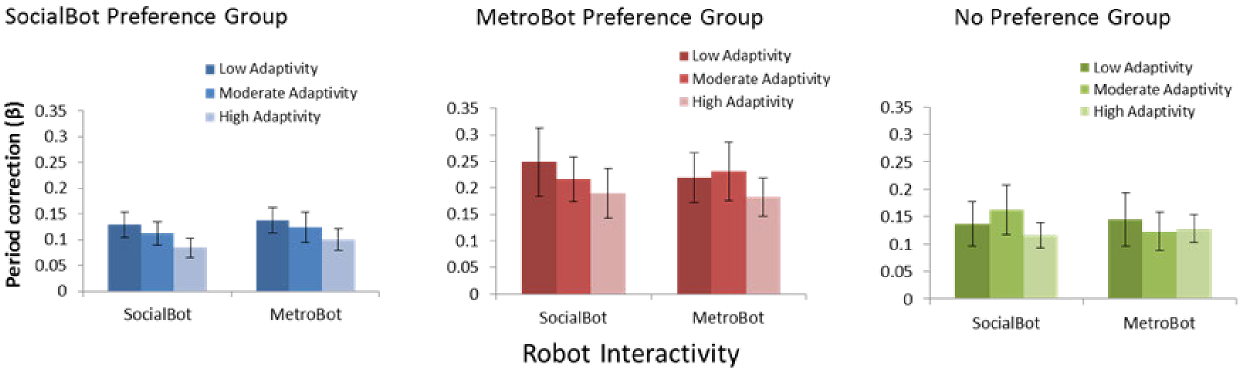
Note: Synchronization accuracy (mean absolute asynchrony) data collapsed across adaptivity levels to display the interaction between the robot interactivity conditions and the participant groups based on the post-task subjective judgement of difficulty. Error bars represent standard errors of the mean.

The ANOVA on synchronization precision (SD asynchronies, Figure 3.4B) showed a main effect of Adaptivity F(2,54) = 20.22, p <.001, ηp2 =.428. Post-hoc pairwise comparisons using a Bonferroni correction showed significantly higher variability in the low adaptivity condition (M = 39.37, SE = 1.8) than both the moderately adaptive condition (M = 34.69, SE = 1.2, Mdiff = 4.68, p <.001) , and the high adaptivity conditions (M = 33.10, SE = .8, Mdiff = 6.27, p <.001). The moderate adaptivity condition also had significantly greater variability than the high adaptivity condition (Mdiff = 1.59, p = .04. There was also a main effect of Post-task Preference group F(2,27) = 5.38, p = 0.11, ηp2 = .285. Bonferroni post hoc comparisons showed that those who found MetroBot easier to synchronize with, displayed less variability (M = 30.18, SE = 2.15) than either those who preferred SocialBot (M = 39.02, SE = 1.9, Mdiff = -8.85, p =.015), or those who perceived no difference in difficulty between the two versions of the robot (M = 37.97, SE = 2.03, Mdiff = -7.79, p = .04). There was no difference between the SocialBot preference or No preference groups. There was no effect of Robot Interactivity, and unlike the accuracy results, there were no interactions.

1.1.1: Model-based parameter estimates of underlying mechanisms.

The analysis of the period correction estimates (Figure 3.6), demonstrated a main effect of adaptivity F(2,54) = 5.43, p = .007, ηp2 = .167, with Bonferroni corrected pairwise comparisons showing that the high adaptivity condition displayed significantly less period correction (M = 1.34, SE = .016) than both the moderate (M = 1.61, SE = .021, Mdiff = -.028, p = .022) and low adaptivity conditions (M = 1.69, SE = .023, Mdiff = -.036, p = .011). This indicates that when the robot was highly responsive, participants corrected for a lower proportion of the asynchrony. There was no main effect of Robot Interactivity or Post-Task Preference Group, nor were there any interactions.

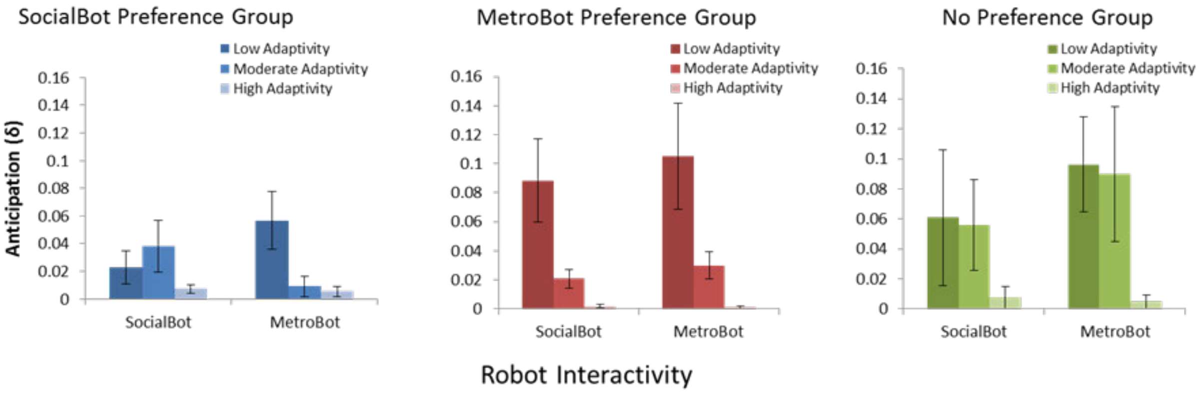
Figure 3.6: Model-based parameter estimates of Period correction



Note: Period correction (β) estimates calculated using ADAM for the three preference groups based on the post-task subjective judgement of task difficulty, split between the interactive robot (SocialBot) and the non-interactive robot (MetroBot) conditions. Error bars represent standard errors of the mean.

The temporal anticipation parameter estimates are shown in Figure 3.7, where it can be seen that there was generally a greater tendency to track rather than predict (values <.5). The ANOVA revealed a main effect of Adaptivity $F(2,54) = 11.24$, p <.001, η_p^2 =.294, with significantly lower anticipation estimates in the high adaptivity condition (*M* = .005, *SE* = .002) than in both the moderately adaptive (*M* = .041, *SE* = .012, M_{diff} = -.036, *p* = .005) and low adaptivity conditions (*M* = .072, *SE* = .016, M_{diff} = -.067, $p < .001$). Participants thus displayed relatively more tracking behaviour (copying the previous inter-onset interval) when the robot was highly responsive. There were again no main effects of Robot Interactivity or Post-Task Preference group, nor any interactions.

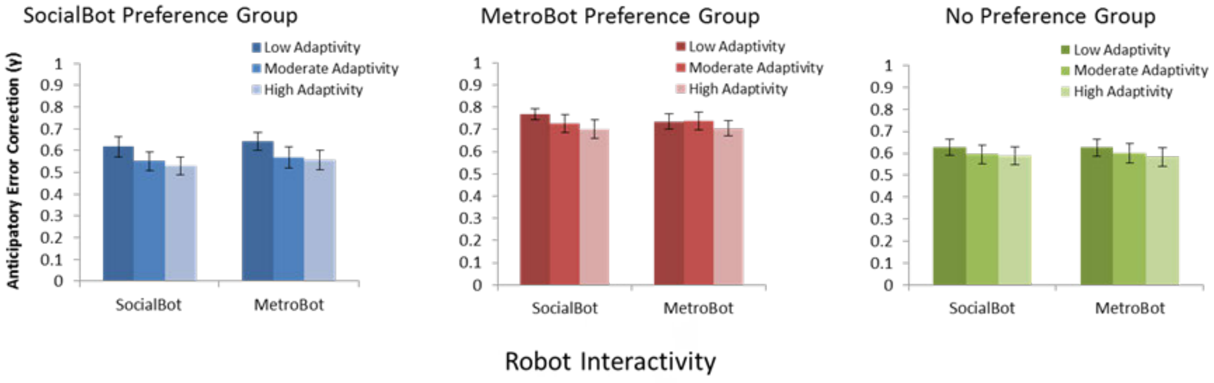
Figure 3.7: Model-based parameter estimates of Anticipation



Note: Estimates of temporal anticipation (δ) calculated using ADAM for the three preference groups based on the post-task subjective judgement of task difficulty, split between the interactive robot (SocialBot) and the non-interactive robot (MetroBot) conditions. Error bars represent standard errors of the mean.

The ANOVA on the measure of anticipatory error correction (Figure 3.8) also found a main effect of Adaptivity $F(2,54) = 31.94$, $p <.001$, $\eta_p^2 =.542$, with significantly less anticipatory error correction in the high adaptivity condition (*M* = .61, *SE* = .024) compared to both the moderate adaptivity (*M* = .63, *SE* = .025, M_{diff} = -.019, *p* = .005) and the low adaptivity condition (*M* = .67, *SE* = .022, M_{diff} = -.059, $p < .001$), and less anticipatory error correction between the moderate and low adaptivity conditions (M_{diff} = -.04, $p < .001$). In addition, there was a main effect of Post-task Preference group $F(2,27) = 3.95$, $p = .031$, $\eta_p^2 =.226$, with the MetroBot preference group employing significantly more anticipatory error correction (M = .73, SE = .04) than either the SocialBot preference group (M = .57, SE = .04, M_{diff} = 1.51, p =.013) and the No preference group (M = .60, SE = .04, M_{diff} = -.125, p =.039). There was no main effect of Robot Interactivity. There was a 2-way interaction between Adaptivity and Post-task Preference group $F(4,54) = 2.81$, p =. 034, η_p^2 =.172, but there were no other significant interactions. The interaction between Adaptivity and Preference group was broken down by collapsing the data across the two Robot interactivity conditions, and a one way repeated measures ANOVA was conducted separately for each Post-Task Preference group.

Figure 3.8: Model-based parameter estimates of Anticipatory error correction



Note: Estimates of anticipatory error correction (γ) calculated using ADAM for the three preference groups based on the post-task subjective judgement of task difficulty, split between the interactive robot (SocialBot) and the non-interactive robot (MetroBot) conditions. Error bars represent standard errors of the mean.

In the ANOVA for the group who preferred SocialBot, there was a significant main effect of Adaptivity F(2,20) =33.09, p <.001., ηp2 = .768, with Bonferroni corrected pairwise comparisons showing that there was significantly less anticipatory error correction employed in the high adaptivity condition (M = .54, SE = .04) compared to the low adaptivity condition (M = .63, SE = .04, Mdiff = -.09, p <.001). The moderately adaptive condition (M = .56, SE = .04) also showed less anticipatory error correction than the low adaptivity condition (Mdiff = -

.07, p <.001). Similarly, the ANOVA for the MetroBot preference group also displayed a main effect of Adaptivity F(2,16) =11.36, p =.001, ηp2 = .587, with significantly less anticipatory error correction being employed in the high adaptivity condition (M = .70, SE = .04) than both the moderately adaptive (M = .73, SE = .04, Mdiff = -.03, p =.014) and the low adaptivity conditions (M = .75, SE = .03, Mdiff = -.05, p =.004). However, in contrast to these two groups, the no preference group displayed no significant effect of adaptivity with no significant differences shown in the amount of anticipatory error correction across all three levels of VP adaptivity.

3.4.2 Preferences as Predictors of Differences in Synchronisation Accuracy

A hierarchical linear regression analysis was performed to determine the contribution of pre-existing and post-task preferences to differences in synchronization accuracy between the two robot versions. Before conducting this analysis, the post-task Metrobot and SocialBot preference groups were collapsed into one group. We did this based on the results of the previous analysis that revealed that there was no difference in accuracy between the two robot versions for the two groups with a directional preference for either SocialBot or MetroBot. By contrast, for those that had no preference for either robot, there was a difference in accuracy between the two different robot versions. Thus, the post-task preferences were reduced to two categories—those that made a directional choice for preferring either robot (*n* = 20) or those that had no preference (*n* = 10). The dependent measure in the regression was the difference score between each robot version for synchronization accuracy (log-transformed mean absolute asynchrony – collapsed across adaptivity levels). The dichotomous post-task categorisation of preference (preference versus no preference) was entered as the first predictor, with the scores on the pre-task 7-point Likert preference rating entered at the second step.

The regression at step 1 found that the post-task preference category on its own is a significant predictor of the difference in synchronization accuracy, $R^2 = .15$, adjusted $R^2 = .12$, $F(1, 28) = 5.01$, $p = .033$. However the addition of the pre-task ratings at step 2 did not significantly improve the model, R^2 change = .03, $p = .34$, and the overall model was no longer significant, $R^2 = .18$, adjusted $R^2 = .12$, $\mathrm{F}(2, 27) = 2.98$, $p = .068$. In this final model, once shared variance was removed, the post-task preference category was the only significant unique predictor, $\beta = .43$, $p = .023$, with pre-task preference ratings not significantly contributing any explanatory power to the model $\beta = .18$, $p = .34$.

3.5 DISCUSSION

To investigate how social characteristics of an interaction partner affect interpersonal rhythmic coordination and the underlying mechanisms that support such coordination, we employed two versions of an adaptive drumming robot as an interaction partner in a sensorimotor synchronization task. To assess the impact of explicit social cues, one version of the robot used communicative actions that encourage joint engagement (‘SocialBot’), while the other version did not (‘MetroBot’). In addition, we assessed the role of implicit cues relating to the responsiveness of the interaction partner by varying the degree of synchronization adaptivity employed by each version of the robot. We also investigated the role of individual differences in personal preference for interaction partner type by grouping participants based on the perceived task difficulty between the different versions of the robot.

As expected, the robot that was socially engaging was judged to be significantly more anthropomorphic, more animate, and more likable. These results are in line with previous studies and confirm that robots that use human social communicative tools are perceived as more human-like and are more enjoyable to interact with (Hortensius & Cross, 2018). Nonetheless, when asked about which robot version was easier to synchronize with, participants had differing perspectives. Despite the objective difficulty for both versions of the robot being equal, only a third of participants judged the two versions as being equally easy to synchronize with. Approximately a third of participants perceived the social robot to be the easier partner, while the remaining third preferred the non-engaging robot. These varying preferences highlight that ‘liking’ an anthropomorphic robot does not necessarily equate to finding an anthropomorphic robot as easier to interact with during a coordination task. This also demonstrates that social-cognitive attributions held within an individual may be more influential than features of the robot (Hortensius & Cross, 2018).

The hypothesis that performance would be better with the socially engaging ‘human-like’ robot was not directly supported. For the most part, accuracy and precision were equivalent with both the socially engaging robot and the robot that did not interact socially. However, there was an interaction between robot Social Interactivity and Post-task Preference group, which showed that for the two groups who found one robot easier than the other, performance was the same irrespective of which robot version they were drumming with. However, for the group that perceived the two versions of the robot as equally difficult to synchronize with, performance was better with the socially engaging robot. This suggests that when there is no strong preference for one robot or the other arising from the drumming experience, the more interactive robot may enhance the joint context, leading to an increased sense of ‘we agency’, which then leads to improved performance. In other words, anthropomorphism may support the establishment of a joint context, leading to improved performance; however, this may be evident to the greatest degree for those who are neutral in regard to preferring the experience of coordinating with more or less interactive partners.

The difference in performance between the two robot versions for only the group who did not perceive any difference in difficulty is also interesting because it shows that the judgement of difficulty is not driven by sensitivity to how well the participants performed during the task. While those who reported that there was no difference in difficulty performed better with SocialBot, those who made a directional choice to one robot version or the other did not perform better with either robot. This result also implies that the demonstrated results in performance are not merely due to demand characteristics, such as participants putting in more effort with the version of the robot that they preferred doing the task with. Additionally, for the no preference group to perform better with the socially engaging robot but not report any difference in subjective difficulty suggests that explicit social communicative cues may affect performance independent of awareness.

Our results demonstrate that the presence (or not) of a directional preference may be a modulating factor. However, whether this difference is driven by pre-existing preferences, for example, a bias toward or against working with technology, or more so preferences that arise during the experience, was an open question. While we showed that robot interactivity had an effect on synchronization accuracy for only those who do not report a clear post-task preference for one robot over the other, when assessing whether it is pre-existing or post-task preferences that contribute to differences in performance, we found that it is only the latter that makes a difference. This suggests that the presence or lack of pre-existing preferences for working with technology do not reliably modulate the effect of robot interactivity on performance. In contrast, it is the difference in preferences that are formed during an experience that may interact with the effect of partner interactivity. It may be that partner preferences are not fully formed until individuals have experience with each partner. Though, the question still remains as to what aspects of the encounter with the two versions of the robot drove the differential formation of experience-based preferences.

An unexpected finding in our results was that the group of participants who judged the static, non-interactive robot (MetroBot) as the easiest to synchronize with were overall significantly better at the task than both the group that did not perceive any difference between the two robot versions and the group that found the interactive robot easier to synchronize with. The ‘MetroBot’ preference group was significantly more accurate and more precise than either of the other groups. It may be that those that are more adept at rhythmic coordination find the addition of social engagement unnecessary for establishing the joint context and thus perceive social cues as needless distractions. Perhaps those who are good at synchronization may perceive the non-interactive robot as more stable and predictable and thus easier to coordinate with. Tay et al. (2014) found greater acceptance of a social robot when the robot displayed non-verbal cues that matched the individual participant's personality. Thus, those who are good at synchronization may have been more focused on the synchronization task itself (rather than the social interaction) and thus perceived MetroBot as ‘matching’ their focus. This unexpected finding presents an interesting avenue for future research into the role of skill in preference formation.

As predicted, joint performance was best when the robot was more adaptive. Synchronisation accuracy and precision increased (lower asynchrony and less variability) as the degree of VP adaptivity increased, indicating that the implicit cue of robot responsiveness was effective in modulating participants’ drumming performance. The improvement in performance with increased adaptivity is in line with previous synchronization studies that use the VP (Fairhurst et al., 2013; Mills et al., 2015, 2019), however, our results extend previous findings by showing that with tempo changing adaptive sequences, performance continues to improve even with high degrees of adaptivity.

While there was some evidence that individual differences in post-task preference modulate performance with the two versions of the robot (better performance for the no preference group with SocialBot compared to MetroBot), we did not see the predicted interaction between post-task preference and adaptivity. This result is in contrast to our previous study (Mills et al., 2019), where the improvement in performance with the more adaptive VP only occurred when interacting with the preferred partner. We suggested that our previous results may have been driven by beliefs about how a human partner will synchronize compared to a computer partner. In the case of the present study, it may be that despite having a version of a 'social' robot, the partner was still clearly not an agent and beliefs about how a robot behaves and the mechanisms that it will employ to synchronize, may not have been counteracted by the socially engaging behaviour. In this case, the explicit cues relating to the commitment and intentionality of the partner may not have been sufficient to modulate the effect of the implicit cue of partner responsiveness. This is an important consideration for human-robot interaction studies—although a robot may display explicit cues indicating commitment and intention, an individual's explicit knowledge that a partner is a machine, not an active agent, will influence the extent to which a 'joint' context can be created (Hortensius & Cross, 2018; Michael & Salice, 2017)

In regard to the parameter estimates of the mechanisms that underpin synchronization, there were no direct effects of the explicit socially engaging robot behaviour. However, as predicted, there was an effect of VP Adaptivity on temporal anticipation, adaptation, and anticipatory error correction. For temporal anticipation, there was relatively less prediction being employed as the robot adaptivity increased, which is in line with our previous study (Mills et al., 2019). The decrease in temporal anticipation as adaptivity increased was accompanied by a similar effect on estimates of error correction, with relatively less period correction being employed in the high adaptivity condition. The effect on period correction extends our previous findings, where we found no effect of VP adaptivity on error correction when looking at only low or moderate levels of adaptivity. Together these results for temporal anticipation and period correction indicate efficiency in effortful processing when the partner is more responsive and taking on more of the burden in order to synchronize. It may be that the implicit cue of responsiveness elicits an increased sense of partner cooperativity leading to modulation of anticipatory and adaptive processes, which benefits performance.

Likewise, for the estimate of anticipatory error correction (where the outcome of one's prediction of other's timing is compared to the motor plan for one's own subsequent movement), for the most part, there is a relative reduction in the amount of anticipatory error correction employed as adaptivity increased. However, this was not the case for the group who perceived no difference in difficulty between the two robot versions. Unlike the SocialBot and MetroBot preference groups, there was no difference in the degree of anticipatory error correction engaged in across the different adaptivity levels. It appears that those who preferred either Socialbot or Metrobot were sensitive to the changes in robot adaptivity and modulated the degree to which they incorporated their prediction of the partners timing. However, those who found both robots as equally easy to synchronize with did not significantly alter how much they incorporated their prediction of the robot's timing into their own action timing as the robot became more responsive.

Taken together, the results of this study are similar to our previous study (Mills et al., 2019) in that participants are sensitive to the implicit cue as to how responsive the partner is during dynamic synchronization and will modulate their behaviour accordingly. Explicit cues, while affecting explicit attitudes and preferences, are not sufficient to elicit a change in coordination performance or the underlying processes that support synchronization. However, we again see evidence that individual differences in preferences that are formed as a result of the interactive experience may modulate the effect of these implicit and explicit cues. Although we did not directly replicate the results of our previous study relating to individual partner preferences, we again showed some differences in synchronization performance based on interaction partner characteristics that were dependant on individuals' subjective post-task preferences. The differences in findings may be due to a lack of power because of the small sample size in each of the preference groups. Further studies that employ larger samples and address the importance of personality, attitudes and biases, as well as post-task subjective judgements, are recommended to try and further understand the complexities of these factors during social dynamics and human-machine interaction.

Other aspects not taken into consideration by the present study that may warrant further investigation include the role of expertise, gender, and personality. The degree of previous exposure or experience with rhythmic coordination tasks (such as musical experience) or experience working with machines may modulate the influence of both implicit and explicit cues as to how responsive and interactive the partner is. Similarly, the role of gender may also be a crucial modulating factor. Recent research has found that females are less likely to trust a robot interaction partner than males (Stanton & Stevens, 2017), and in the case of the present study, there were four times as many females as males, which may have lessened the likelihood of a straightforward effect of robot interactivity. Interestingly, four out of the six males in the final sample of the present study preferred MetroBot (one of the remaining males preferred SocialBot, while the other had no preference), which suggests that perhaps males may have a bias toward a more mechanical partner, however with so few males in this study, no inferences can be drawn relating to gender and robot preferences. A future study may investigate whether there are gender differences, not only in performance with the different robot versions but in subjective post-task preferences. Perhaps explicit social cues that promote engagement may have a more substantial effect on females than males by actively increasing trust. Finally, addressing the role of personality factors such as locus of control or leader/ follower tendencies (Fairhurst et al., 2014) may help shed further light on the role of individual differences.

In conclusion, the characteristics of a synchronization partner affect performance during interpersonal rhythmic coordination, even when the agency of the partner is not in question. Implicit cues indicating the responsiveness of an interaction partner appear to be more influential than more overt and explicit communicative signals when it comes to synchronization performance. Nonetheless, the incorporation of explicit social communicative cues to robot behaviour does lead to greater anthropomorphication and liking of the robot. In addition, individual differences in subjective judgements of how difficult it is to coordinate with the different versions of the robot interact with whether or not the social engagement or joint context has an influence on rhythmic coordination. We found that robot interactivity influenced performance, however, only for those who did not form a post-task preference for either robot version. This suggests that top-down processes may modulate basic sensorimotor processes that support synchronized movement and highlights the importance of individual differences when considering social dynamics—the context or characteristics of an interaction partner will have a different influence on different types of people (Hortensius & Cross, 2018; Tay et al., 2014). Thus, individual differences are an important consideration when designing interactive robots—our results suggest that there is an advantage of social engagement for those who are neutral in preferences; however, not all will prefer to work with an anthropomorphic machine, and therefore engineers should incorporate flexibility into robot design (Rau et al., 2009). Although complex, further understanding of the role of individual differences is important for future research into social interaction and interpersonal coordination.

Chapter 4: Partner Intentionality Affects Neural Alpha Oscillations that Reflect Self-Other Integration and Segregation During Rhythmic Interpersonal Coordination

4.1 ABSTRACT

The intentionality of a co-actor can influence performance during rhythmic interpersonal coordination. To better understand this influence, the current study investigated the effect of partner intentionality on the cognitive-motor and neural mechanisms that underpin synchronisation performance. Neural oscillations within the alpha frequency over sensorimotor regions have been shown to reflect the representation of a co-actor during joint action, and thus may be influenced by partner intentionality. EEG sensorimotor alpha activity was measured while participants drummed in time with a computer-controlled adaptive virtual partner (VP) that was programmed to respond to the participant with various degrees of adaptivity (error correction) during tempo-changing pacing sequences. In addition, task instructions were manipulated so that participants were told they were synchronising with either another person or a computer. It was observed that there was greater sensorimotor alpha suppression during synchronisation with the belief of the computer partner compared to the human partner. Additionally, at the level of the cognitive-motor mechanisms that support synchronisation, there were effects for both the explicit social instruction and VP adaptivity, which together suggested greater self-other integration during the computer partner instruction and conversely greater self-other segregation in the human partner instruction. Overall, the results of the current study indicate that top-down processes relating to social context are reflected in sensorimotor alpha suppression indexing the balance between self-other integration and segregation during rhythmic interpersonal coordination.

4.2 INTRODUCTION

The ability to temporally coordinate movement with others is necessary to enable the successful completion of many types of joint tasks. Social neuroscience has begun to investigate the neural mechanisms underpinning such coordinated movement using a variety of brain imaging and electrophysiological techniques. Such studies have identified particular networks of brain regions showing specific patterns of activation when performing a task with another person as opposed to performing a task alone or with a machine (Fairhurst et al., 2014; Kokal et al., 2009; Naeem et al., 2012b; Novembre et al., 2014). From a cognitive perspective, the ability to have a representation of a co-actor's actions in one's mind is a necessary pre-requisite for ongoing coordinated movement and behaviours (Sebanz, Bekkering, et al., 2006). Such co-representation allows for mental simulation (Welsh et al., 2020), which enables accurate prediction of a co-actor's forthcoming movements.

There are various theoretical perspectives relating to the specific neural mechanisms that support co-representation and action understanding, including proposals concerning the mirror neuron system (Iacoboni, 2009; Kaplan & Iacoboni, 2006; Rizzolatti & Craighero, 2004), the action observation network (Cross et al., 2009; Gallese, 2005) and common coding (Hommel et al., 2001; Sebanz & Knoblich, 2009). A commonality between these perspectives is that they posit specific neural processes that underlie the ability to represent the actions of others during joint action. One issue that remains unresolved within all accounts is how these neural processes are affected by whether the co-actor is an intentional partner who is firstly capable and secondly intends to coordinate.

A promising technique that has been employed to examine changes in neural activity during interpersonal coordination is electroencephalography (EEG) (Dumas et al., 2010; Konvalinka et al., 2014; Novembre et al., 2016; Sänger et al., 2012; Tognoli & Kelso, 2015).

Studies employing EEG have found that neural oscillations arising from sensorimotor areas of the brain within the alpha frequency band—often defined as between 8–12 Hz—may be particularly related to tasks that are conducted in conjunction with another person (Hobson & Bishop, 2016). This particular type of alpha frequency is also referred to as the mu frequency, and modulations within this frequency band have been found during both perception and action during joint tasks over sensorimotor regions of the brain.

The mu frequency is generally recorded from areas of the scalp corresponding to sensorimotor regions of the cortex (e.g. C3 and C4) and was originally associated with movement (Hari, 2006; Pfurtscheller & Neuper, 1994). When a person is at rest, populations of neurons in these regions fire in synchrony, resulting in characteristic mu waves or rhythms being observed. However, when an action is either performed or imagined, neurons in these sensorimotor regions become desynchronised, leading to a decrease in observed mu power, and this is referred to as ‘mu desynchronization’ or ‘mu suppression’ (Pineda, 2005). It is inferred that such suppression reflects greater activity in these sensorimotor brain regions (Pfurtscheller & Lopes, 1999), and importantly has been demonstrated during social coordination tasks. Accordingly, mu suppression has been proposed as a neural correlate reflecting the co-representation of a co-actor during joint interpersonal activity (Kourtis et al., 2010). The term ‘mu suppression’ is most commonly used in the literature within joint action research and refers to activity within the frequency band in comparison to a resting baseline. The phrase ‘sensorimotor alpha’ is also sometimes used and refers more so to modulations in power and is not necessarily compared to a resting baseline. In this chapter, I use the term ‘mu suppression’ when discussing previous work so as to match the terminology chosen by previous authors. However, when referring to the present study, I use the term ‘sensorimotor alpha’ because this more accurately reflects that the study employs an active control baseline rather than a resting baseline.

Early findings indicated that sensorimotor mu or alpha suppression was uniquely related to execution or imagination of one's own actions; however, such suppression has since been demonstrated also to occur when merely observing the actions of others (Arnstein et al., 2011; Oberman et al., 2007; Pineda, 2005). These findings have led to the mu frequency band being considered a signature of the neural system that underpins action understanding and co-representation of others' actions (Hari & Salmelin, 1997; Hobson & Bishop, 2017). It is theorised that when observing the actions of another, similar neural processes in motor regions occur as if one is also enacting this same movement. This motor resonance enables mental simulation of others actions and occurs when the movement comes from one's own movement repertoire and is positively correlated with movement expertise (Calvo-Merino et al., 2005; Cross et al., 2006; Wu et al., 2016). The ability to simulate another's actions based on one's own motor system is particularly important for joint actions requiring temporal coordination (Keller et al., 2007; Sebanz & Knoblich, 2009; Vesper et al., 2013, 2017) as it facilitates a greater understanding of another's goals and intentions, which promotes accurate prediction of the time course of the unfolding actions.

In addition to action observation in the visual domain, mu suppression has also been observed in the auditory domain, suggesting that representations of a co-actor's actions can also be based on auditory information. For example, Pineda et al. (2013) found greater mu suppression in the left hemisphere when exposed to sounds related to physical actions (i.e. paper ripping) compared to control sounds. Similarly, Wu et al. (2016) found that listening to piano melodies evoked mu suppression in expert pianists, indicating that action representation can also be elicited when listening to sounds that are produced by others. The proposal that auditory information informs the representation of others' actions is consistent with a broader body of research demonstrating that audio-motor integration plays a vital role in music performance (Zatorre et al., 2007), and like visual information, mu suppression may be a signature of this auditory co-representation.

There is also evidence to show that mu suppression is related to behavioural performance during joint coordination tasks. Greater mu suppression was found when participants were asked to synchronise finger taps with another person compared to when they tapped their fingers at their own pace and did not coordinate (Naeem et al., 2012b). Similarly, Tognoli et al. (2007) found mu suppression in dyads making synchronised finger movements and could distinguish synchronised movement from unsynchronised movement in two different peaks within the mu range (which they termed phi$_1$ and phi$_2$). Likewise, Naeem et al. (2012a) found modulations in upper and lower mu frequencies depending on the coordination context (self-paced, in-phase, or anti-phase coordination). These findings suggest that the mu frequency band may reflect the integration of mutual representations of both self and other during temporal interpersonal coordination of movement.

In addition to the mu frequency being related to self-other integration, there is also evidence that modulations within the alpha frequency may be an index of the balancing between self-other integration and self-other segregation. While the integration of representations for self and other is a fundamental part of interpersonal coordination, it is also necessary to maintain a distinction between actions initiated by self and those produced by others (Keller et al., 2014). For example, in musical ensemble performance, each musician must integrate information related to their own part with the parts of other musicians to monitor the overall sound while simultaneously maintaining segregation between their own output and that of others. This process of balancing self-other integration and segregation enables the effective functioning of cognitive-motor mechanisms that facilitate precise yet flexible interpersonal coordination by allowing co-performers to anticipate, attend, and adapt to each other’s actions in real-time (Keller et al., 2016).

Novembre et al. (2016) identified particular patterns of neural oscillations within the alpha frequency band over central parietal regions reflecting the degree of self-other integration and segregation during joint musical performance. Pairs of pianists were asked to play short two-part musical duets that had either been previously rehearsed or not, with either congruent or incongruent tempo-change instructions for the second part of the musical piece. The results showed that during the first part of the familiar piece, when the tempo instructions were congruent, there was greater self-other integration (indexed by temporal synchrony), even before the actual tempo change took place. In addition, this effect was accompanied by greater degrees of sensorimotor alpha suppression. Conversely, when joint performance was less synchronous, there was alpha enhancement rather than suppression. These findings suggest that when interpersonal timing is highly synchronous, there is more of a focus on external information leading to greater integration between representations of self-other; and this is reflected in alpha suppression.

On the other hand, when interpersonal timing is less synchronous, this requires a greater focus on internal knowledge and more segregation between self and other; and this is reflected in increased alpha activity. Thus, the degree of synchronisation and desynchronisation within the alpha frequency band may index the regulation between self-other integration and segregation (Novembre et al., 2016). These findings lend support to the idea that modulations in sensorimotor alpha activity in central parietal regions relate to self-other representation during interpersonal coordination.

In addition to joint motor activity, mu suppression has been associated with a variety of higher-order social behaviours such as joint attention (Lachat et al., 2012), imitation (Dumas et al., 2012), and is related to social- cognitive abilities such as empathy (Gutsell & Inzlicht, 2010). Additionally, information about the social context and relevance of an action can modulate mu suppression. For instance, differences in spatial orientation and attention of a co-actor during an interactive setting can induce greater degrees of mu suppression compared to a non-interactive setting (Ensenberg et al., 2017; Oberman et al., 2007; Perry et al., 2011). Likewise, perceiving the actions of an interactive partner compared to a non-interactive partner produces greater mu suppression (Kourtis et al., 2010). Furthermore, it has been shown that individuals with social deficits such as Autism Spectrum Disorders show attenuated mu suppression when observing actions (Dumas et al., 2014; Perkins et al., 2010), again suggesting that this neural frequency band may be associated with processes that support social interaction.

Given that sensorimotor alpha and mu suppression are related to the representation and coordination of movement with others, and also social-cognitive processes, one question that arises is—is it necessary that the interaction partner is viewed as an active, intentional being? Numerous behavioural studies have found modulations in performance when interacting with an intentional agent compared to an unintentional agent such as a computer or a robot (e.g. Atmaca et al., 2011; Mills et al., 2019; Obhi & Hall, 2011b; Tsai et al., 2008; Wykowska et al., 2015), and it is argued that a non-intentional co-actor is not represented in the brain in the same way as an intentional co-actor (Kokal et al., 2009; Naeem et al., 2012b). Thus, when interacting with an unintentional partner, alpha suppression may not be observed to the same degree.

Findings related to the influence of partner intentionality on alpha and mu suppression have been mixed. Konvalinka et al. (2014) asked pairs of participants to synchronise finger taps and found greater suppression of oscillations in the low alpha range (~10hz) when synchronising with a human partner than with an isochronous sequence of sounds played by a computer. These results suggest that sensorimotor alpha suppression is specifically related to representing the actions of intentional coordination partners. In contrast, Urgen et al. (2013), while finding greater mu suppression during action observation, found no differences between observations of either human or robotic actions. Thus, it is unclear whether the neural representation of other's actions differs between either intentional or unintentional partners and whether alpha or mu suppression is an index of these differences.

A further question that arises when considering the effect of partner intentionality is—what is the impact of individual differences in social preferences? The previous studies in this thesis identified that at a behavioural and cognitive level, individual preferences could differentially modulate synchronisation performance with different types of partners. While, at the level of the brain, social-cognitive neuroscientists have also identified specific patterns of brain activity associated with individual preferences and biases during social interaction. For example, using fMRI, Molenberghs et al. (2013) found that perceptual judgements differed between observation of in-group members compared to out-group members. These differences in judgements were associated with increased neural activity within the inferior parietal lobule when observing in-group members, indicating that biases can be reflected at the level of neural activity, and this activity is modulated by the social context. Furthermore, the identified differences occurred during early perceptual processing rather than during later decision-making stages, which suggests that the influence of biases may occur below the level of conscious processing.

The influence of biases has also been demonstrated in neural electrical activity. For example, Gutsell and Inzlicht (2010) found greater degrees of mu suppression during the observation of actions produced by in-group members compared to out-group members. Moreover, this effect was compounded by individuals' prejudices and further exacerbated when out-group members belonged to disliked groups. These results indicate that action co-representation may only occur for those that are perceived as 'like me' and that personal preferences or biases for or against a particular type of partner may modulate the basic neural processes that underpin simulation and social coordination. It is thus of interest to not only investigate if modulations in the portrayed intentionality of a partner during a joint synchronisation task will be reflected in changes at a behavioural, cognitive, and neural level but also to assess if these changes are modulated by individual differences in preferences and attitudes towards interacting with humans compared to computers.

To investigate the above questions, the main aim of the present study was to examine the impact of partner intentionality on rhythmic interpersonal coordination at three levels of analysis—the level of behavioural performance; the level of the cognitive-motor mechanisms that underpin synchronisation performance; and at the level of the brain—and importantly to better understand the relationship between these three levels. To do this, we used EEG to measure neural oscillations within the alpha frequency band over sensorimotor regions during a rhythmic coordination task, with the instruction of synchronising with either a human partner or a computer-generated sequence of sounds containing gradual tempo changes. In reality, participants were always synchronising with an adaptive virtual drumming partner (VP) set to various degrees of adaptivity (e.g. Mills et al., 2019).

Previous studies assessing mu or alpha suppression have typically employed a passive control condition or a brief interval preceding each trial as a relative baseline. However, changes in attentional engagement associated with these baseline methods can produce large-scale variations in alpha power, and it has therefore been suggested that within-trial baseline methods (where the stimuli or responses change during the course of a trial) are more appropriate for computing suppression effects (Hobson & Bishop, 2016). Within-trial baselining methods were not viable in the current study because constant conditions were required throughout trials in order to assess behavioural performance and to compute ADAM parameter estimates. Hence, in order to obtain a valid measure of relative alpha suppression/ enhancement between conditions, the high adaptivity condition was used as an active baseline control. It can be noted that the high adaptivity virtual partner produces the most stable and reliable performance and therefore provides a suitable active control for a baseline comparison.

Behavioural performance was assessed through measures of synchronisation accuracy and precision, while the ADaptation and Anticipation Model (ADAM) (see chapter 1; Harry & Keller, 2019; van der Steen & Keller, 2013) was used to estimate the cognitive-motor mechanisms that support rhythmic interpersonal coordination. Within ADAM, there are three modules that represent temporal adaptation, temporal anticipation, and anticipatory error correction which are instantiated as estimates of representations for self, representations of other, and the integration between these representations of self and other, respectively. The degree that these mechanisms influence synchronisation quality is affected by beliefs about the intentionality of a co-performer (Mills et al., 2019). Specifically, the aim here was to better understand how the social context may differentially influence the representations of both self and other, as well as the integration between self-other representations during joint drumming. Furthermore, the aim was also to test whether modulations within sensorimotor brain activity and synchronisation performance, based on the social context, are related to specific cognitive-motor processes, or whether the effects are independent of these.

At the level of neural electrical activity, the previous literature suggests that mu and sensorimotor alpha suppression index co-representation and simulation of a co-actor's actions during a joint task. Additionally, modulations in mu and sensorimotor alpha suppression have been associated with various social-cognitive processes during social interaction; and several findings have suggested that an intentional co-actor is not represented in the brain in the same way as a non-intentional co-actor. Thus, to the extent that sensorimotor alpha suppression is a neural correlate reflecting heightened action representation and simulation of an intentional co-actor during joint interpersonal activity, it was hypothesised that there would be greater sensorimotor alpha suppression during synchronisation with the instruction of a human partner rather than the computer partner.

At a behavioural level, in the two previous behavioural experiments within this thesis (see chapters 2 and 3), both implicit and explicit cues were used to imply the intentionality and commitment of an interaction partner. Firstly, it was found that the implicit cue of partner intentionality—how adaptive a drumming partner was—reliably produced modulations in synchronisation performance. Specifically, in chapter 2, synchronisation improved as the VP implemented moderate degrees of adaptivity; and in chapter 3, these findings were extended by showing that performance was further improved with higher degrees of adaptivity, with the most stable and accurate performance occurring when the VP simulated a highly responsive synchronisation partner.

Secondly, explicit cues—either the direct instructions relating to whether the partner was a human or a computer, or explicit social behaviours of a robot— had an effect on synchronisation performance that was dependent upon individual differences in post-task partner preference. In chapter 2, it was found that while synchronisation improved with the moderately adaptive partner compared to the less adaptive partner, this was only the case when participants were synchronising with the partner congruent with their choice of preferred partner. In other words, individuals who rated the human partner as easier to synchronise with showed improved performance with the moderately adaptive VP when instructed that their partner was a human, but not when told their partner was a computer. Similarly, those who rated the computer as easier to synchronise with improved only with the belief of a computer partner and not a human partner.

In contrast, in chapter 3, we found that synchronisation performance was unaffected by robot interactivity for those who had a directional preference for either an interactive or non-interactive robot. However, for those who had no preference for either of the robot versions, performance was better when synchronising with the interactive robot. It appears that individual differences in preference for interacting with a particular partner type may affect the extent to which partner intentionality or social engagement influences performance. What is not clear is the specific role these underlying preferences or biases play and how such individual differences are reflected in neural activity associated with social processes. Thus, to better understand the impact of individual differences in biases or preferences, the second aim of the current study was to further investigate the modulating role of individual differences in partner preferences and pre-existing attitudes toward technology.

At the behavioural level, in accordance with the findings reported in chapters 1 and 2, it was hypothesised that higher degrees of VP adaptivity would improve synchronisation performance. Also, in line with the previous findings, it was predicted that partner preferences—derived from post-task individual judgements of which partner is easier to synchronise with—will interact with the portrayed social context to differentially modulate synchronisation performance. The exact direction of this effect is difficult to predict due to the mixed findings of the previous studies. On the one hand, individuals may perform better with their preferred partner (e.g., chapter 2), while on the other hand, the social instruction may have an effect only for those without a directional preference (e.g., chapter 3). Likewise, based on studies that have shown that individual biases may influence performance in joint tasks, it was also predicted that individuals' pre-existing attitudes toward technology may be related to any effect of social instruction.

At the level of the cognitive-motor mechanisms, in line with the previous experiments in this thesis (see chapters 2 & 3), it was predicted that the implicit cue of VP adaptivity would lead to a reduction in the use of temporal anticipation and anticipatory error correction. It was further hypothesised that modulations in sensorimotor alpha suppression and in behavioural performance would be accompanied by modulations in the cognitive-motor mechanisms that support synchronisation.

4.3 METHOD

4.3.1 Participants

In total, 37 participants took part in the study (32 females; *M* =23.79 years, *SD* = 7.18). The participants were predominately students from Western Sydney University who participated in return for course credit or were volunteers from the university community who participated in return for travel reimbursement of $40. The majority of participants (*n*=34) had very little musical experience (< 2 years); however, three participants reported having 6-10 years of musical training. Eleven participants were removed from the analysis—four guessed the true nature of the experiment, four recorded insufficient drumming data (see data analysis), and technical issues during the EEG recording resulted in unusable EEG data for three participants—leaving 26 participants (22 females) in the final sample. The experiment was approved by the university's human research ethics committee, and all participants provided informed written consent. Participants were debriefed at the conclusion of data collection.

4.3.2 Design

The study employed a (2 x 3) x 3 mixed design, with two within-subjects variables and one between-subjects variable. The first within-subjects variable was the degree of VP adaptivity. There were three levels—low adaptivity, moderate adaptivity, and high adaptivity. Based on the previous studies conducted within this program of research, the high adaptivity condition will objectively produce the most stable and accurate performance and may be inferred as the easiest condition. This condition will serve as an active control condition in the

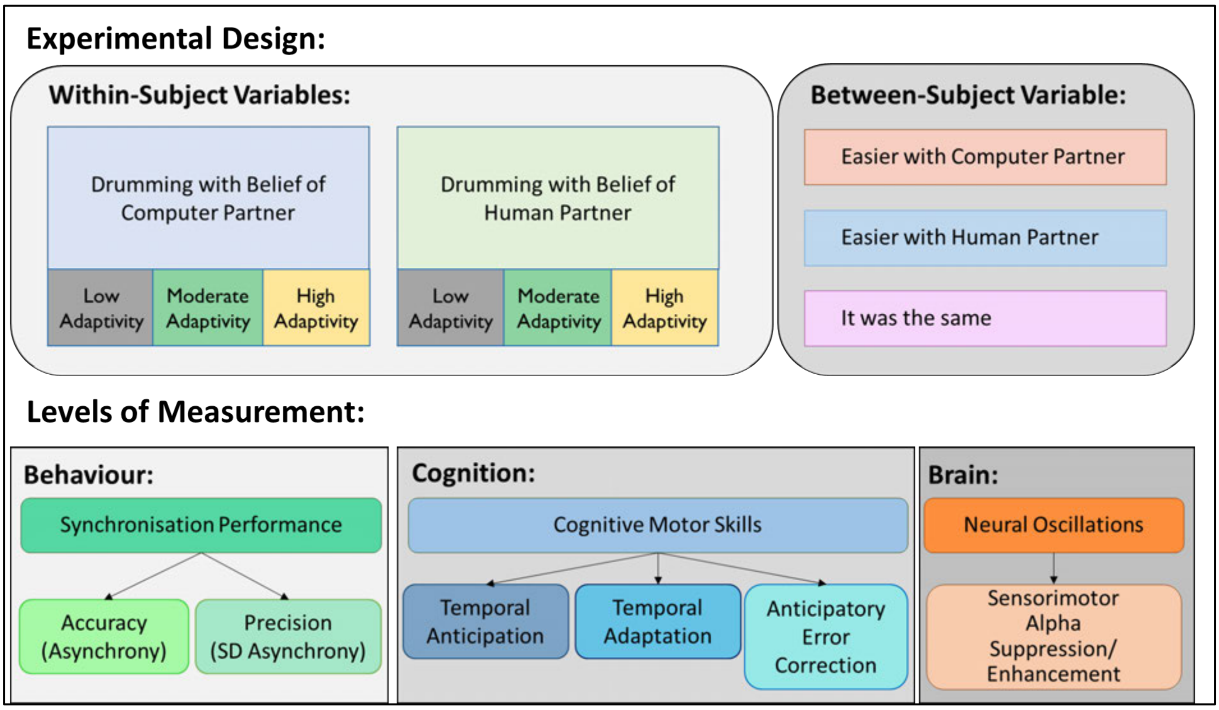
EEG analysis to account for the effect of the drumming movement on EEG activity, allowing relative sensorimotor alpha power in the low and moderate adaptivity conditions to be determined. The second within-subjects variable was the social instruction referring to whether the participants were told they were drumming with either a human or computer partner. Finally, the between-subjects variable was partner preference which was based on participants' responses to the post-task forced-choice question "Was it easier to synchronise with your human partner or with the computer partner?" The response options were 'The human partner', 'The computer partner', or 'It was the same' (as in Mills et al., 2019).

The effect of each of these variables will be evaluated at three levels of dependant measures (see Figure 4.1). Firstly, at a behavioural level, synchronisation performance in each condition will be assessed with measures of synchronisation accuracy and precision. Secondly, at a cognitive-motor level, estimates of the three core underlying mechanisms that facilitate synchronisation, namely temporal anticipation, period correction, and anticipatory error correction, will be examined. Finally, the third level of dependant measure relates to the electrical activity of the brain, specifically, modulations within sensorimotor alpha activity.

4.3.3 Materials

EEG data were collected in an electrically shielded, sound-attenuated booth, which was adjacent to a central control room. A second sound-attenuated booth was positioned on the opposite side of the central control room and was used as the supposed location for the second 'participant' (a confederate). Participants sat on a custom-made wooden chair in the EEG booth and used a wooden drumstick with a nylon tip to drum with their right hand on a Yamaha DTX TP70S drum pad, which was attached to a metal drum stand in front of the participant. The drum pad was connected via a wall conduit to a Roland TD-9 Percussion Sound Module that was situated in an adjacent control room. The sound module was

Figure 4.1: Schematic of the experimental design.



Note: There were three independent variables, including two within-subjects variables— the degree of VP adaptivity (low, moderate, and high adaptivity) and the explicit social instruction (human partner or computer partner); and a between-subjects variable—post-task partner preference (prefer human, prefer computer, no preference). This was based on participants' subjective judgements of which social instruction condition was the easiest. The dependant measures were assessed at three levels of analysis—behaviour (synchronisation accuracy and precision), cognition (comprised of estimates of temporal anticipation, temporal adaptation, and anticipatory error correction), and the brain (relative sensorimotor alpha activity).

connected to a Motu Microlite MIDI interface, which was in turn connected to an Acer laptop running Windows software. This laptop presented the auditory stimuli and recorded the drumming data using a custom-made C++ program. The stimuli were presented binaurally through Etymotic ER-1 insert headphones with disposable foam tips that were inserted into each ear canal. These headphones were connected to the Acer laptop. End-to-end latency measures taken prior to the experiment revealed a constant mean delay of 60ms (*SD* = .9ms) between a drum tap occurring and the tap being recorded by the program and a sound signal being sent by the program and the sound being produced through the headphones. As the delay was constant, this issue was addressed by using the C++ program to account for the delay by subtracting 60ms from the tap registration times. The stimulus computer also sent triggers via an Arduino device to a separate acquisition computer (a Dell 7060 desktop computer), which recorded the EEG data.

Practice trials were completed outside the sound-attenuated booths on a Roland Handsonic 10 percussion pad. Participants also completed the *Attitude Toward Computers Inventory* (ATCI; Shaft, Sharfman, & Wu, 2004) to assess their pre-existing preferences for interacting with computers.

4.3.4 Stimuli

The stimuli were auditory sequences of percussion sounds (as used in Mills et al., 2019 and Mills et al., under review – see chapters 2 and 3). Each sequence started with four synthesized cowbell sounds, followed by 60 synthesized woodblock sounds (tones) with a clear onset and rapid decay. A beep indicated the end of the trial. The sequences progressed through tempo variations that accelerated and decelerated following a sinusoidal function. Inter-onset intervals (IOIs) within these sequences varied between 500 and 600ms, with step sizes of lengthening and shortening intervals varying between 1 and 32ms.

In addition to these tempo variations, the adaptive function of the VP was applied to implement phase correction. This adaptive function simulates human error correction processes by correcting the timing of the upcoming VP sound by a proportion (α) of the asynchrony between the last sound and the corresponding drum tap produced by the participant (see Repp and Keller, 2008). Three levels of adaptivity were used, $\alpha = .1$ (low adaptivity), $\alpha = .4$ (moderate adaptivity), and $\alpha = .7$ (high adaptivity). A linear phase correction model based on Vorberg and Shulze (2002) controlled this process with the algorithm:

$$t_{n+1} = t_n + T + a \times async,$$

where t_n = time of pacing event, $T =$ base IOI (drawn from the tempo changing sequence), a = phase correction parameter implemented by the computer (.1, .4, or .7), and $async =$ asynchrony between tap and pacing event. For example, if a participant tapped too early relative to the previous tone (a negative asynchrony), the subsequent event would occur earlier by a proportion (.1, .4, or .7) of that asynchrony. Thus, each IOI throughout the tempo changing sequence was adjusted in response to the amount and direction of the asynchrony associated with the last tap.

4.3.5 EEG Recording

EEG was continuously recorded using an Active Two BioSemi amplifier (www.biosemi.com) at 512Hz from 64 Ag/ AgCl electrodes, following the international 10/20 system. The electrode-offset level was kept below 50k ohm to ensure adequately low electrode impedance, and the recorded electrode signals were referenced to the Common Mode Sense (CMS) electrode. Four additional electrodes were positioned above and below the right eye and lateral to the eyes to monitor vertical and horizontal eye movements, and two additional mastoid electrodes were placed behind each ear.

4.3.6 Procedure

A confederate was employed to create the illusion that a human was the drumming partner for each participant. The participant and the confederate would arrive together and were instructed at the same time. The two ‘participants’ were told that the purpose of the experiment was to investigate brain activity when synchronising with another person. They were shown the two sound-attenuated booths that they would be seated in and told that they would be drumming in time with each other while we monitored the electrical activity of their brains. They were also told that a series of baseline recordings would be recorded while each participant drummed along with a sequence of sounds played from a computer. In reality, the participant was always drumming with the computer-controlled VP and not the human confederate.

Before entering the sound-attenuated booths, the participant and the confederate completed three practice trials where they drummed together on a tapping pad (each striking a different area of the tapping pad). For these trials, a tempo-changing sequence was played through speakers, and the participants were asked to drum in time with each other and the tempo-changing sequence (which was non-adaptive). The participants were asked to note the tempo changes and to replicate these in the joint drumming trials. Each ‘participant’ was then directed to each sound-attenuated booth where the EEG set up took place. The experimenter accompanied the participant into one booth, while a second confederate acting as an additional researcher would accompany the other confederate ‘participant’ to the second booth. Without the participant’s awareness, once the door of the sound-attenuated booth was closed, both confederates left the second booth.

While the electrodes were fitted, participants completed a series of questionnaires, including the ATCI (Shaft et al., 2004) and provided demographic information. Once the electrodes were fitted, participants completed six blocks of trials, each comprising ten auditory sequences, with 60 trials in total and ten trials of each condition. The duration of each sequence was approximately 32s. Three blocks were with the ‘human partner’ instruction, and three were with the ‘computer partner’ instruction. For each instruction type, there was a block of each level of VP adaptivity—low adaptivity ($\alpha = .1$), moderate adaptivity ($\alpha = .4$), and high adaptivity ($\alpha = .7$). The order of delivery of the six blocks was counterbalanced with some constraints. Firstly, participants completed two consecutive blocks of either the human instruction or the computer instruction at each of the low and moderate levels of adaptivity, and then two blocks with the alternative partner instruction at either the low and moderate levels of adaptivity. The high adaptivity condition was always delivered in the final two blocks, again with counterbalanced order of the partner instruction. We delivered the high adaptivity conditions in the final blocks to ensure that the experience of synchronising with the highly adaptive partner did not influence performance with the low and moderately adaptive conditions to allow direct comparison to Experiment 1 (Chapter 2), and so that the EEG data obtained from the high adaptivity condition would serve as an active control condition in the analyses of sensorimotor alpha power.

At the end of the experiment, participants were given a final questionnaire assessing their belief of the cover story and assessing their explicit beliefs and preferences for which type of partner is easier to synchronise with.

4.3.7 Behavioural Data Analysis

Data were initially screened for missing taps or taps that were outside a pre-defined boundary of acceptable asynchrony in MATLAB. This boundary was defined as an asynchrony of more than ± half the current IOI (Mills et al., 2019). Linear interpolation was used to correct missing taps or taps with a large asynchrony; however, trials that contained more than three such instances were excluded from the analysis. To be included in the final analysis, at least three valid trials within each condition were required for each participant. Prior to all analyses, a preliminary Analysis of Variance (ANOVA) of all measures confirmed there were no effects of condition order for either the partner social instruction or the degree of VP adaptivity. There was also no relationship between the presentation order of conditions and the post-task subjective preference indicating which condition was easiest. For all analyses, effects are reported as statistically significant at $p < .05$.

A (2 x 2) x 3 ANOVA was conducted on each of the behavioral dependent measures. These measures included indices of synchronisation performance (synchronisation accuracy and precision) and estimates of each of the underlying mechanisms that support synchronisation (temporal adaptation, anticipation, and anticipatory error correction). Synchronisation accuracy (mean absolute asynchrony) was calculated by subtracting the onset time of the participant's tap from the onset time of the tone generated by the VP program, whereas synchronisation precision was indexed (inversely) by the SD of asynchrony. Both measures (mean absolute asynchrony and SD asynchrony) were calculated for each trial and then averaged across all corresponding trials within each experimental condition. Prior to averaging, a log transformation was applied to absolute asynchrony in each of the six conditions to correct for violations of normality.

As in chapters 2 and 3, estimates of temporal adaptation, anticipation, and anticipatory error correction were calculated using the ADAM Model—developed by van der Steen, Jacoby et al. (2015). This computational model comprises an adaptation module, an anticipation module, and a module that integrates adaptation and anticipation—referred to as the joint module. The adaptation module generates a parameter estimate of the amount of period correction that the participant is engaging in. Period correction is an intentional response to a perceived tempo change that adjusts the rate of the internal timekeeper (Repp & Keller, 2004). Model estimates of period correction are calculated based on a linear autoregressive error correction model and represent the degree to which an individual adjusts the period of the internal time-keeper by a proportion of the most recent asynchrony.

The anticipation module produces a parameter for temporal anticipation of sounds produced by another individual (in this case, the VP), which is instantiated as the weighted sum of both predictive (linear extrapolation based on the previous two inter-onset intervals) and tracking processes (where the previous inter-onset interval is copied and repeated). An anticipation estimate of .5 represents that equal prediction and tracking is being employed, whereas values greater than .5 represent relatively more prediction than tracking, and values less than .5 reflects relatively more tracking.

The parameter for anticipatory error correction is computed by a joint module that compares the output of the adaptation module (timing of next planned movement) to the output of the anticipatory module (prediction of other's—i.e., the VP's—next produced sound) and corrects for a proportion of the difference between the two. In principle, this allows a predicted asynchrony between a tap and a tone may be corrected before it occurs. When the anticipatory error correction value is close to 0, the next movement is driven more so by the output of the adaptation model (one's own motor plan). As this parameter becomes closer to 1, the output of the anticipation module (prediction of other's sound) is increasingly incorporated into the timing of the next movement; thus, the prediction of the other's timing has more influence over the planned timing of the next movement (see Harry & Keller, 2019; van der Steen, Jacoby et al., 2015, for more details).

Parameter estimates were calculated for each participant separately for each trial. This entailed fitting ADAM to the empirical behavioral data from each trial using a bounded Generalised Least Squares method (see Jacoby et al., 2015; van der Steen, Jacoby et al., 2015). These parameter estimates were then averaged across corresponding trials within each condition.

4.3.8 EEG Analysis

The EEG data were processed using LetsWave6 (https://www.letswave.org/) and Matlab (The MathWorks, USA). Continuous data were segmented into 30-second epochs beginning from the last lead in tone within each sequence (see Stimuli). A bandpass filter (Butterworth, fourth-order) was applied between 0.1 Hz and 45 Hz. To attenuate noise in the EEG signal caused by electrical signals emitted from the drum pad, a band-stop filter was applied at 50 Hz (with the addition of harmonics at 100 Hz and 150 Hz). Each electrode was referenced to the average of all electrodes. Independent component analysis was used to identify and remove any artefacts caused by eye movements or head movements related to the drumming movement (Jung et al., 2000). A Fast Fourier Transformation was applied, and the mean power was calculated between 8 and 12 Hz for each electrode and for each participant.

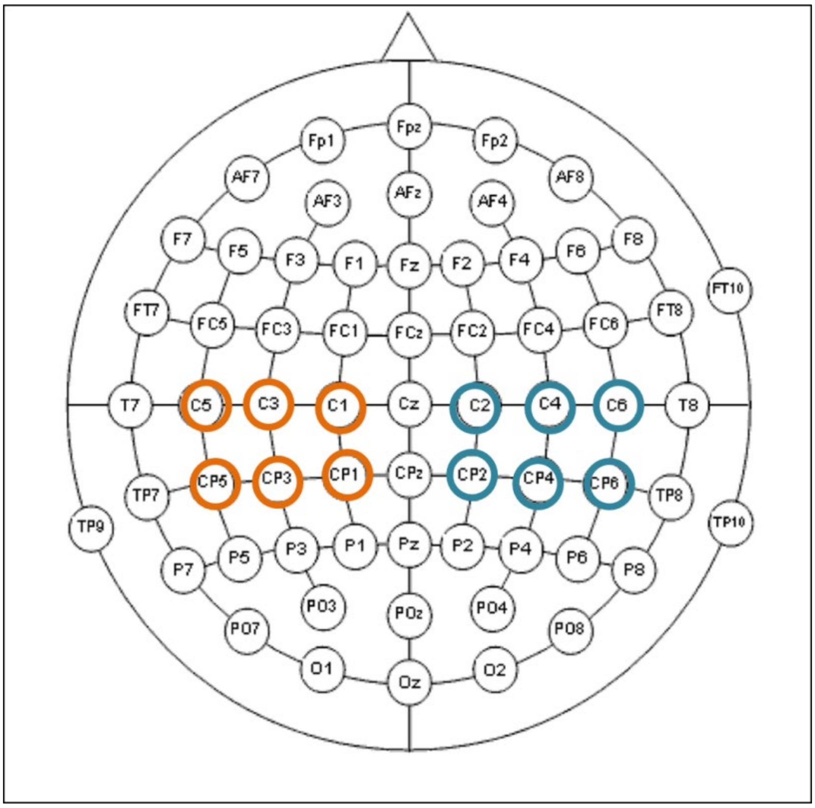
To determine relative sensorimotor alpha suppression, we used the high adaptivity VP condition as an active control condition as a basis for comparison with the low and moderate levels of adaptivity. This condition has been demonstrated to produce the most stable and accurate performance in earlier work using the VP (see chapters 2 & 3; Mills et al., 2018) and thus serves as a suitable baseline that takes into account the effect of the drumming movement on EEG activity. A log of the power ratio (LPR) between the low and moderate adaptivity conditions over the high adaptivity condition (the active control condition) was calculated separately for the human partner and computer partner conditions as an index of relative alpha suppression /enhancement. The LPR is a useful estimate of sensorimotor alpha attenuation as it corrects for variability in absolute alpha power as a result of individual differences such as scalp thickness, electrode placement, and impedance, as opposed to differences in brain activity (Oberman et al., 2007). The LPR is thus defined as:

$$LPR = \log(\frac{A}{B})$$

Where ‘A’ represents the low or moderate adaptivity conditions in each of the human and computer partner conditions, and ‘B’ represents the commensurate high adaptivity condition as the active control condition.

Mu suppression is generally considered as the ratio between a passive baseline and an experimental condition. However, in the context of the current study, this is not appropriate because the main experimental conditions are active to the extent that they entail drumming actions. Thus, using the high adaptivity condition as an active control condition accounts for participants’ motor activity. This alternative approach allows for the assessment of the relative differences between the levels of adaptivity and the social instruction conditions. Finally, to estimate alpha ratios across sensorimotor regions separately for each hemisphere, the mean LPR from electrodes C1, C3, C5, CP1, CP3, and CP5 were averaged together to form an average left hemisphere sensorimotor alpha power ratio, and electrodes C2, C4, C6, CP2, CP4, and CP6 were averaged for the right hemisphere estimate (see Figure 4.2). Hemisphere is included as a factor because participants were drumming with their right hand, and thus differences were expected between left and right sensorimotor regions. A 2 (Hemisphere) x 2 (VP adaptivity) x 2 (Social Instruction) ANOVA was then conducted.

Figure 4.2: The EEG Montage showing the central-parietal electrode clusters used in the analysis.



Note: Electrodes C1, C3, C5, CP1, CP3, and CP5 were averaged to form a left central-parietal cluster (represented in orange), while electrodes C2, C4, C6, CP2, CP4, and CP6 were averaged to form a right central-parietal cluster (represented in blue).

4.4 RESULTS

4.4.1 Synchronisation performance

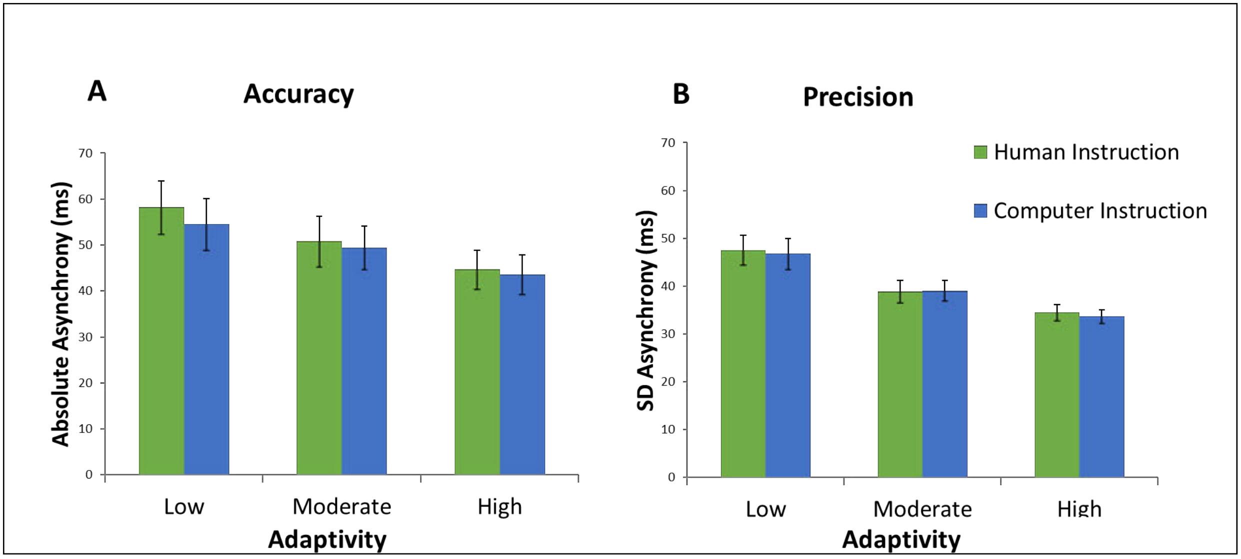
To assess the effects of VP adaptivity, the social instruction, and post-task partner preferences at the behavioural level, a (3 x 2) x 3 ANOVA was conducted on the two measures of synchronisation performance—accuracy (mean absolute asynchrony) and precision (SD asynchrony). The two repeated measures factors included the degree of VP adaptivity with three levels—Low ($\alpha = .1$), Moderate ($\alpha = .4$) and High ($\alpha = .7$), and the explicit social instruction with two levels—Human partner instruction and Computer partner instruction. The between-subjects factor reflected participants' reported post-task subjective partner preferences gauged by their selection of which partner type was easier to synchronise with. There were three separate groups—Prefer human partner ($n = 9$), Prefer computer partner ($n = 7$), and a No preference group ($n = 10$). The means and SD for each performance measure in the two conditions, divided by the three preference groups can be seen in Table 4.1.

The ANOVA on log-transformed absolute asynchrony revealed a significant main effect of VP adaptivity (see Figure 4.3A), $F(2,46) = 31.39$, $p < .001$, $\eta_p^2 = .577$. As hypothesized, Bonferroni corrected post-hoc comparisons showed there was significantly lower asynchrony (greater accuracy) in the high adaptivity condition ($M = 44.17$, $SE = 3.02$) than both the moderately adaptive condition ($M = 50.11$, $SE = 3.48$, $p < .001$) and the low adaptivity condition ($M = 56.35$, $SE = 3.84$, $p < .001$), and the moderately adaptive condition also displayed significantly smaller asynchronies than the low adaptivity condition ($p = .002$). There was no significant main effect of either the social instruction or preference group ($p > .05$), but there was a significant 2-way interaction between VP adaptivity and preference group, $F(4,46) = 3.08$, $p = .025$, $\eta_p^2 = .211$).

Table 4.1: Average synchronisation performance (accuracy and precision) for the social instruction and VP adaptivity conditions (alpha), divided by each preference group.

Conditions			**Synchronisation Performance**			
Social Instruction	**Adaptivity (Alpha)**	**Preference Group**	**Accuracy (Abs Asynchrony)**		**Precision (SD Asynchrony)**	
			Mean	**SD**	**Mean**	**SD**
Human	.1	Prefer Human	54.634	21.278	44.798	9.185
		Prefer Computer	49.446	13.430	47.489	10.340
		No Preference	67.558	24.299	50.091	14.810
	.4	Prefer Human	50.387	24.852	37.503	7.164
		Prefer Computer	45.163	20.957	39.502	10.721
		No Preference	55.146	17.036	39.833	9.217
	.7	Prefer Human	50.653	20.114	35.232	3.984
		Prefer Computer	36.004	12.462	33.983	9.694
		No Preference	45.499	11.202	34.194	4.825
Computer	.1	Prefer Human	54.287	24.494	46.215	8.869
		Prefer Computer	45.408	12.803	45.497	9.383
		No Preference	61.045	21.818	48.167	16.306
	.4	Prefer Human	47.723	18.794	38.849	6.314
		Prefer Computer	41.988	11.777	39.266	6.608
		No Preference	56.129	19.138	39.138	10.321
	.7	Prefer Human	47.554	20.231	34.194	4.196
		Prefer Computer	33.738	8.732	32.587	5.726
		No Preference	46.975	14.031	33.992	5.670

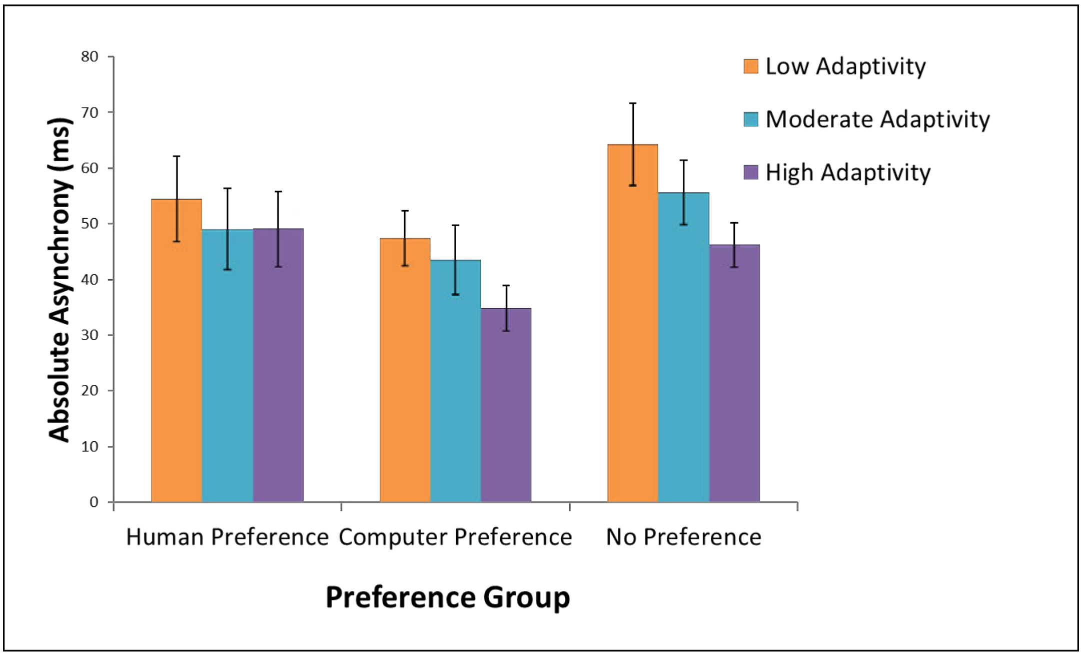
Figure 4.3: Mean Synchronisation Performance



Note: Measures of synchronisation performance for each level of adaptivity between the two Social Instruction conditions. (A) - Synchronisation Accuracy (Mean Absolute Asynchrony, untransformed). (B) - Precision (SD Asynchrony). Error bars represent standard errors of the mean.

The interaction between VP adaptivity and preference group was investigated by running a simple effects analysis to examine the effect of VP adaptivity separately for the three preference groups, using a pooled error term and a manual Bonferroni correction accounting for the three simple effects (adjusted $a = 0.017$). These analyses revealed a simple main effect of VP adaptivity for all three preference groups (human preference group $F(2,46) = 5.73$, $p = .013$, computer preference group $F(2,46) = 15.80$, $p < .001$ and the no preference group $F(2,46) = 13.79$, $p < .001$), with improved accuracy as VP adaptivity increased; however, the rate of improvement differed between the groups (see Figure 4.4). Simple contrasts using a Sidak correction indicated that while the no preference group showed significantly greater accuracy between each successively higher level of VP adaptivity (low-moderate $p = .022$, moderate-high $p = .011$, low-high $p < .001$), the human preference group was significantly more accurate (lower abs asynchrony) in both the moderate and high adaptivity conditions compared to the low adaptivity condition (*p* =.001 and *p* =.018, respectively), but did not display a difference in accuracy between the moderate and high adaptivity conditions. Whereas the computer preference group showed significantly greater accuracy in the high adaptivity condition compared to both the low (*p* =.001) and moderate adaptivity conditions (*p* =.006), but no significant difference between the low and moderate adaptivity conditions.

Figure 4.4: The Interaction Between VP Adaptivity and Preference Groups for Synchronisation Accuracy



Note: Shown here is the interaction between VP adaptivity and the three preference groups for synchronisation accuracy (mean absolute asynchrony, shown here untransformed). Error bars represent standard errors of the mean.

These effects are not straightforward to interpret but might suggest differing degrees of sensitivity to partner adaptivity across groups. Specifically, participants without a preference for a human or computer partner apparently show the greatest overall sensitivity, participants with a preference for a human partner show the greatest sensitivity at low-to-moderate adaptivity (which is the amount of adaptivity most commonly observed in humans; Mills et al., 2015), and participants with a preference for computers were more responsive to higher degrees of adaptivity. Nonetheless, the overall general direction of improvement in synchronisation accuracy was the same across the three preference groups, with better performance during the high adaptivity condition compared to the low adaptivity condition. There were no other significant 2-way interactions, nor was there a 3-way interaction.

The ANOVA assessing SD asynchrony (inversely related to synchronisation precision) also found a main effect of VP adaptivity (see Figure 4.3B) $F\ (2,46) = 63.85$, $p <.001$, $\eta_p^2 =.735$. Precision significantly improved as adaptivity increased, with significantly less variability (lower SD asynchrony) in the high adaptivity condition ($M =34.03$, $SE = 1.1$) compared to both the moderate ($M =39.02$, $SE = 1.62$, $p <.001$) and low adaptivity ($M =47.04$, $SE = 2.35$, $p <.001$) conditions, and also significantly lower variability in the moderate condition compared to the low adaptivity condition ($p <.001$). However, unlike the above analysis, there were no other main effects and no interactions.

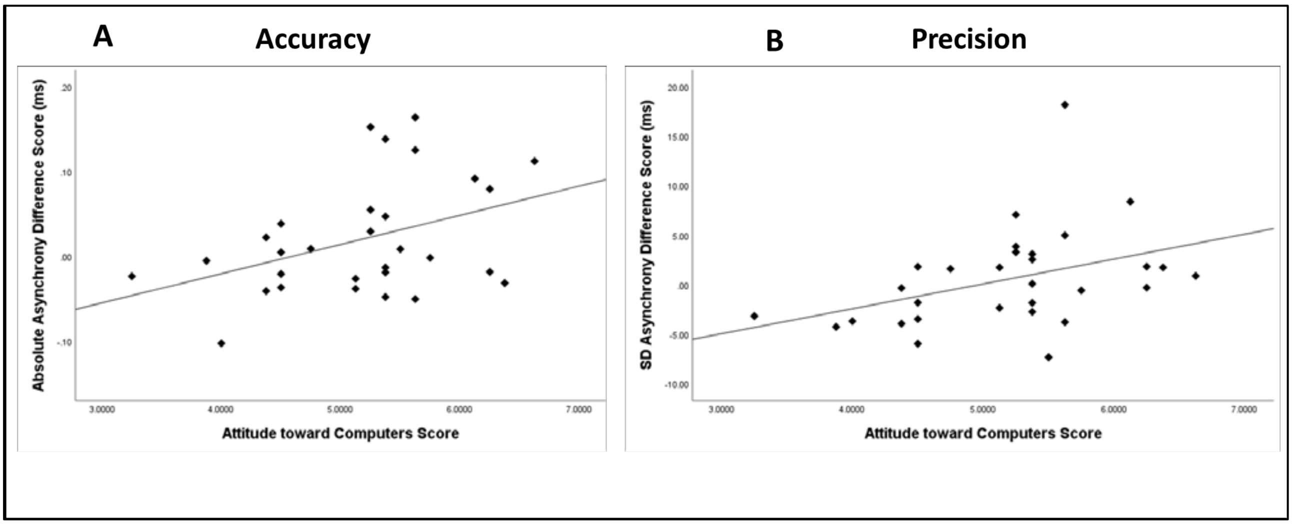
4.4.1.1 Individual differences in attitude toward technology.

In contrast to what was hypothesised and the previous studies within this thesis, there was no clear effect of subjective partner preference on synchronisation performance and no interaction with social instruction. This may be due to the small and somewhat uneven group sizes for each preference group. To further examine if individual differences in pre-existing attitudes and biases influenced the effect of social instruction on performance, a secondary analysis was conducted assessing whether pre-existing attitudes toward computers related to differences in drumming performance between the two social instruction conditions. Specifically, bi-variate regressions were conducted to ascertain if attitude toward computers could predict individual differences in synchronisation accuracy and precision between the human and computer social instruction conditions.

Difference scores were calculated for each of the performance measures by collapsing data across the three levels of adaptivity separately for the human and computer partner conditions and subtracting the computer partner instruction measure from the human partner instruction measure for each participant. A negative difference score thus reflects better performance (i.e. relatively higher accuracy and lower variability) in the human partner instruction condition, and a positive score reflects better performance with the computer. Scores on the *Attitude Toward Computers Inventory* (ATCI) were used as the predictor in the two regressions, with higher scores indicating a more positive attitude toward computers.

The regression relating to the synchronisation accuracy difference score (see Figure 4.5A) found that attitude toward computers was a significant predictor of differences in synchronisation accuracy between the human partner and computer partner conditions $R = 0.40$, $R^2 = 0.16$, adjusted $R^2 = 0.13$, $F\,(1, 28) = 5.43$, $p = 0.027$. Similarly, the regression that assessed differences in synchronisation precision also found that attitude to technology was a significant predictor of differences in precision between the human partner and computer partner conditions $R = 0.40$, $R^2 = 0.16$, adjusted $R^2 = 0.13$, $F\,(1, 28) = 5.26$, $p = 0.029$, (Figure 4.5B). The direction of these relationships suggests that a more positive attitude toward computers is related to better performance (higher accuracy and lower variability) during the computer partner instruction, whereas a less positive attitude towards technology relates to better performance during the human partner condition. In other words, individual differences in attitudes towards computers can account for 16% of the variability in differences in synchronisation performance when synchronising with the belief of either a human or computer partner.

Figure 4.5: The Relationship Between Attitude Towards Computers and Differences in Synchronisation Performance Within the Social Instruction Condition



Note: A higher difference score reflects better performance (i.e., relatively higher accuracy and lower variability) in the computer partner instruction condition. (A) Attitude toward computers can predict differences in synchronisation accuracy, with more positive attitudes relating to higher accuracy in the computer instruction condition. (B) Attitude toward technology can also predict differences in synchronisation precision with more positive attitudes to computers relating to higher precision in the computer condition.

4.4.2 Model-based parameter estimates of the core cognitive-motor mechanisms

To assess the effects of the three independent variables (VP adaptivity, the explicit partner instruction, and post-task partner preferences) on the cognitive-motor mechanisms that support synchronisation, a (3 x 2) x 3 ANOVA was conducted on each of the modelling estimates generated by the ADAM model. This included separate analyses for each of the parameter estimates, including period correction, temporal anticipation, and anticipatory error correction. The means for the parameter estimates for each VP adaptivity and social instruction condition, divided by the three preference groups, can be seen in Table 4.2.

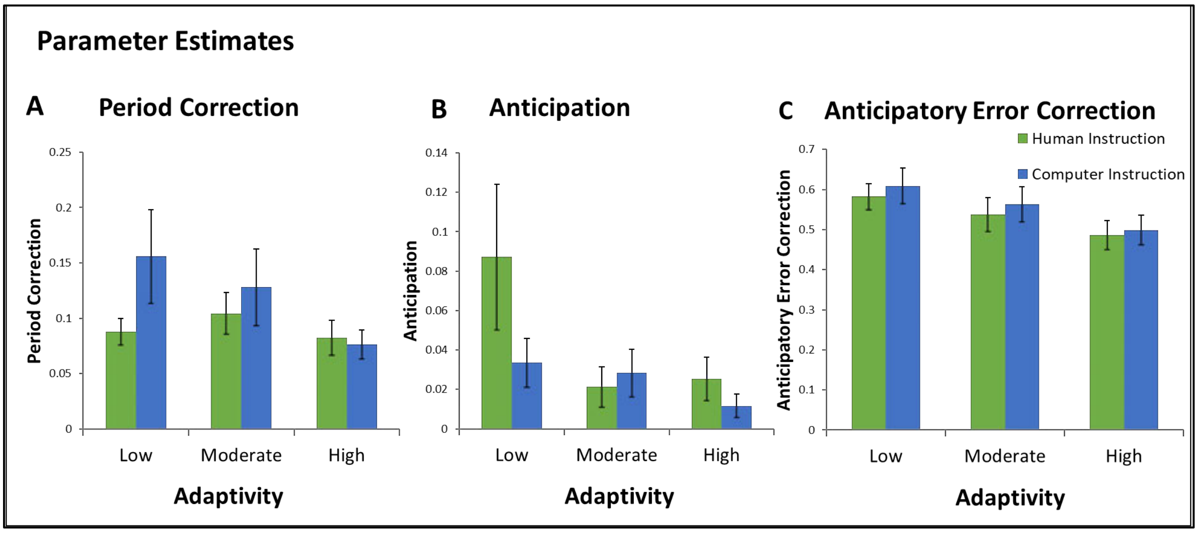
Table 4.2: Average parameter estimates generated by the ADAM for period correction, temporal anticipation and anticipatory error correction for the social instruction and adaptivity conditions divided by each preference group.

Conditions			**Parameter Estimates**					
Social Instruction	**Adaptivity (Alpha)**	**Preference Group**	**Period Correction**		**Temporal Anticipation**		**Anticipatory Error Correction**	
			Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Human	.1	Prefer Human	0.101	0.056	0.090	0.073	0.608	0.104
		Prefer Computer	0.088	0.028	0.062	0.082	0.594	0.061
		No Preference	0.077	0.044	0.102	0.208	0.551	0.164
	.4	Prefer Human	0.121	0.087	0.011	0.021	0.553	0.172
		Prefer Computer	0.110	0.079	0.040	0.067	0.545	0.156
		No Preference	0.086	0.048	0.017	0.018	0.518	0.162
	.7	Prefer Human	0.084	0.084	0.033	0.048	0.483	0.147
		Prefer Computer	0.095	0.056	0.036	0.054	0.507	0.153
		No Preference	0.071	0.033	0.012	0.021	0.475	0.129
Computer	.1	Prefer Human	0.200	0.183	0.035	0.064	0.647	0.149
		Prefer Computer	0.178	0.184	0.033	0.032	0.641	0.133
		No Preference	0.101	0.107	0.032	0.041	0.553	0.198
	.4	Prefer Human	0.134	0.107	0.023	0.019	0.606	0.168
		Prefer Computer	0.167	0.213	0.009	0.012	0.558	0.145
		No Preference	0.096	0.062	0.047	0.068	0.530	0.181
	.7	Prefer Human	0.085	0.063	0.010	0.016	0.523	0.157
		Prefer Computer	0.091	0.047	0.003	0.007	0.516	0.129
		No Preference	0.058	0.027	0.019	0.032	0.465	0.132

The ANOVA on the period correction estimates (Figure 4.6A) demonstrated a main effect of VP adaptivity, $F(2,46) = 8.23$, $p < .001$, $\eta_p^2 = .264$, with the high adaptivity condition ($M = .081$, $SD = .01$) displaying significantly less period correction than both the moderate ($M = .119$, $SD = .02$, $p = .005$) and low adaptivity conditions ($M = .124$, $SD = .02$, $p = .002$), but there was no difference between the low and moderate adaptivity conditions. This indicates that when the VP was highly adaptive, participants corrected for a lower proportion of the previous asynchrony in the timing of their subsequent drum stroke. There was no significant main effect of social instruction or preference group, however, there was a significant 2-way interaction between VP adaptivity and social instruction (a Greenhouse

Geisser correction was applied due to a violation of sphericity), *F*(1.66, 38.2) = 4.99, *p* = .016, η_p^2 = .179. Simple effects analysis revealed that at the low VP adaptivity level, there was significantly less period correction employed when participants were told they were interacting with the human partner rather than the computer partner (*p* = .021), but there were no differences between the social instruction conditions at moderate and high adaptivity levels. There were no other interactions.

Figure 4.6: Mean Parameter Estimates



Note: Shown here are the model-based parameter estimates calculated using ADAM, for each level of adaptivity (Alpha) between the two Social Instruction conditions. A- Period Correction, B- Temporal anticipation, and C-Anticipatory error correction. Error bars represent standard error of the mean.

The ANOVA of the anticipation estimates (Figure 4.6B) also revealed a main effect of VP adaptivity (Greenhouse Geisser corrected), *F* (1.25,28.67) = 5.62, *p* = .019, η_p^2 = .196. Relatively more anticipation was employed in the low adaptivity condition (*M* =.059, *SD* = .017) than in both the moderate (*M* =.024, *SD* = .006, *p* = .034) and the high adaptivity conditions (*M* =.019, *SD* = .005, *p* = .015), but there was no difference between the moderate and high adaptivity conditions. There was also a main effect of social instruction F (1,23) = 7.69, *p* = .011, η_p^2 = .250, with significantly more anticipation employed during the human partner instruction (*M* =.045, *SD* = .011), than the computer partner instruction condition (*M* =.023, *SD* = .006). There was no effect of preference group and no interactions ($p > .05$).

The ANOVA on the measure of anticipatory error correction (Figure 4.6C) also found a main effect of VP adaptivity $F(2,46) = 42.24$, $p <.001$, $\eta_p^2 =.647$, with significantly less anticipatory error correction in the high adaptivity condition (*M* =.505, *SD* = .027) compared to both the moderate adaptivity (*M* =.449, *SD* = .031, $p < .001$) and the low adaptivity conditions (*M* =.401, *SD* = .027, $p < .001$), and significantly less anticipatory error correction in the moderate condition compared to the low adaptivity condition ($p = .001$). There was no significant effect of social instruction or preference group, nor were there any interactions.

4.4.3 The relationship between synchronisation performance and the underlying core cognitive-motor mechanisms

To further understand how the underlying cognitive-motor mechanisms of synchronisation are related to synchronisation performance (absolute asynchrony and SD asynchrony) in each of the social instruction conditions, a series of hierarchical regressions were conducted. All data were collapsed across the three levels of VP adaptivity to yield a single mean for each of the social instruction conditions (human and computer partner). Separate regressions were then conducted for the two social instruction conditions and the two measures of performance, with the parameter estimates from the ADAM model (period correction, temporal anticipation, and anticipatory error correction) from the commensurate condition used as predictor variables. In all regressions, the order of variable entry was period correction, followed by temporal anticipation and finally, anticipatory error correction.

Table 4.3 displays the standardised regression coefficients (β) and R^2 change (ΔR^2) for the predictors at each step within all four hierarchical regressions. The first two regressions were conducted to predict synchronisation accuracy (absolute asynchrony) in each of the human and computer instruction conditions. For the human partner instruction condition, at step 1, the overall regression model revealed that period correction alone is a significant predictor of absolute asynchrony. The addition of temporal anticipation at step 2 did not significantly improve the model, nor did the addition of anticipatory error correction at step 3 (see Table 4.3). The final overall model with all three parameter estimates was significant, $R = 0.75$, $R^2 = 0.57$, adjusted $R^2 = 0.52$, $F\,(3, 25) = 11.39$, $p < .001$ accounting for 57% of variance in the absolute asynchrony difference score. Once shared variance was removed, period correction was the only significant unique predictor throughout all steps of the regression (see table 4.3).

Table 4.3: Hierarchical Multiple Regression between the parameter estimates of Period Correction, Temporal Anticipation and Anticipatory Error Correction as predictors of Synchronization Accuracy (Mean Absolute Asynchrony) and Precision (SD Asynchrony).

	Absolute Asynchrony				**SD Asynchrony**			
	Human Instruction		Computer Instruction		Human Instruction		Computer Instruction	
Parameters	β	ΔR^2	β	ΔR^2	β	ΔR^2	β	ΔR^2
Step 1	-	.51***	-	.39***	-	.46***	-	.28**
Period Correction	-.71***		-.62***		-.69***		-.53**	
Step 2	-	.01	-	.09	-	.15***	-	.06
Phase Correction	-.71***		-.58***		-.69***		-.49***	
Temporal Anticipation	.05		.30		.07		.25	
Step 3	-	.06	-	.18**	-	.41***	-	.57***
Phase Correction	-.46*		-.15		.21		.28**	
Temporal Anticipation	.04		.19		.04		.06	
Anticipatory Error Correction	.43		.62***		1.1***		1.12***	

***$p < .001$. **$p < .01$. * $p < .05$

The regression for absolute asynchrony in the computer instruction condition followed a somewhat different pattern. Again, at step 1, period correction alone generated a significant predictive model, and temporal anticipation did not significantly improve the model at step 2. However, unlike the human partner condition, anticipatory error correction did significantly improve the predictive utility of the final model $R = 0.80$, $R^2 = 0.65$, adjusted $R^2 = 0.61$, F (3, 25) = 16.19, p <.001, with the final model explaining 65% of the variance in absolute asynchrony. Period correction was again a unique predictor at steps 1 and 2; however, unlike the previous regression, once shared variance was removed, anticipatory error correction is the only unique predictor in the final overall model (see Table 4.3). This suggests that the use of period correction alone predicts differences in synchronisation accuracy when participants believe that their partner is a human; however, when instructed that they are synchronising with a computer, the use of anticipatory error correction is more predictive of differences in synchronisation.

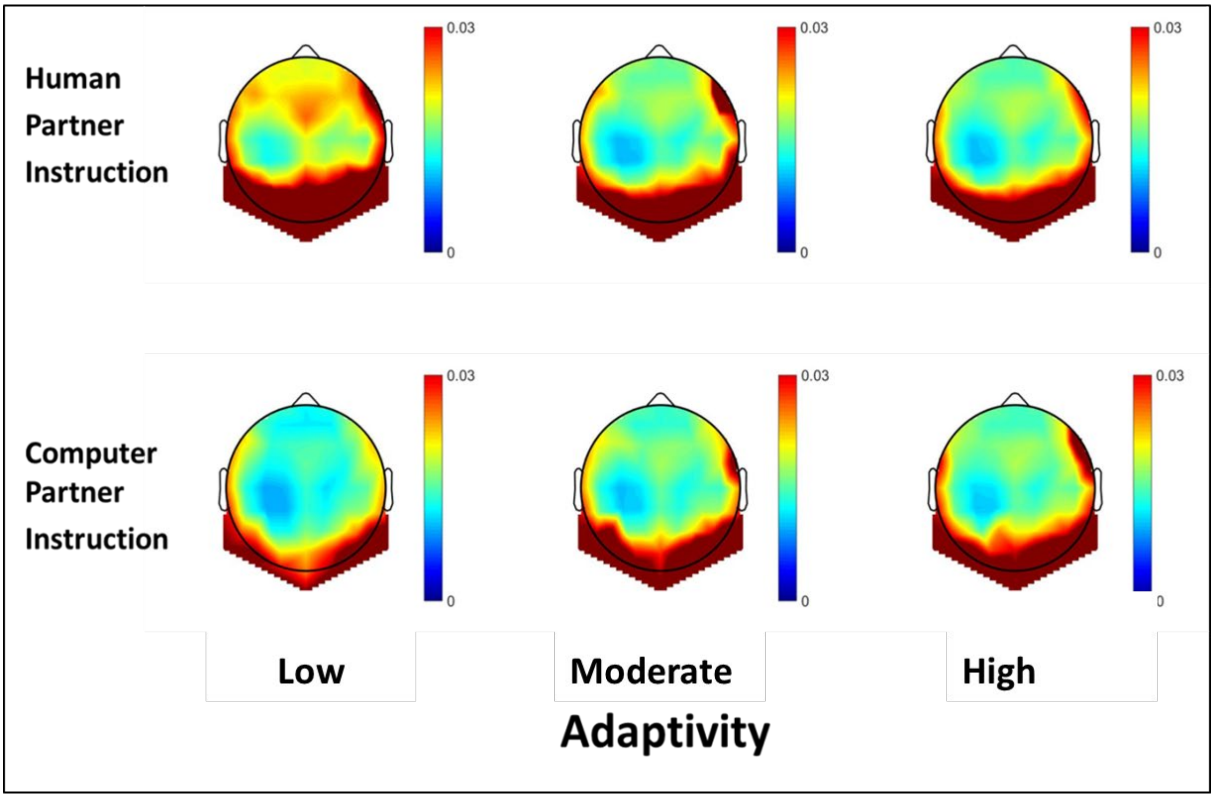
In regards to synchronisation precision (SD asynchrony), the regression in the human condition found at the first step that period correction was sufficient to generate a significant predictive model. The addition of temporal anticipation at step 2 did not offer any improvement, however at step 3, the model was significantly improved with the inclusion of anticipatory error correction $R = 0.95$, $R^2 = 0.89$, adjusted $R^2 = 0.88$, F (3, 25) = 74.65, p < .001 and accounted for 89% of variance in synchronisation precision. After accounting for shared variance, period correction is a marginally significant unique predictor (p = .057); however, anticipatory error correction largely accounts for the vast majority of variance (p <.001 – see table 4.3).

A similar pattern of results was found in the computer partner instruction condition for synchronisation precision. At step 1, period correction can significantly account for the variance in synchronisation precision. Temporal anticipation did not improve the model, whereas the addition of anticipatory error correction significantly improved the predictive utility of the final model, $R = 0.95$, $R^2 = 0.91$, adjusted $R^2 = 0.90$, $F\ (3, 25) = 90.99$, $p < .001$, explaining 91% of the variance in synchronisation precision. Once shared variance was removed, both period correction and anticipatory error correction emerged as significant unique predictors of synchronisation precision (see table 4.3). These results suggest that both period correction and anticipatory error correction contribute to synchronisation stability, which is similar within both partner instructions.

4.4.4 Sensorimotor Alpha Suppression

The spatial similarity across within-subject factors (collapsed across all preference groups) can be seen in Figure 4.7, which displays topographical plots of EEG power in the alpha frequency band (8 – 12hz) across both within-subject factors of VP adaptivity and social instruction. To remove any confounding effect of the participant's drumming movement, a log of the power ratio (LPR) between the sensorimotor alpha power for the low and moderate VP adaptivity conditions was calculated by dividing each by the high adaptivity conditions to create an LPR representing relative alpha suppression/ enhancement in each condition. As previously mentioned, the high VP adaptivity condition has been previously demonstrated to produce the most stable and accurate performance (see chapters 2 & 3; Mills et al., 2019), and this was again demonstrated in the current results with the highest synchronisation accuracy and precision in the high adaptivity condition. Additionally, in regards to period correction, temporal anticipation, and anticipatory error correction (which are assumed to be effortful), the current results showed that, in all three, there were relatively lower estimates in the high adaptivity condition. Together these results suggest that the high adaptivity condition was indeed the least demanding, and thus analogous to a baseline condition and serves as a suitable active control that takes into account the effect of the drumming movement on EEG activity.

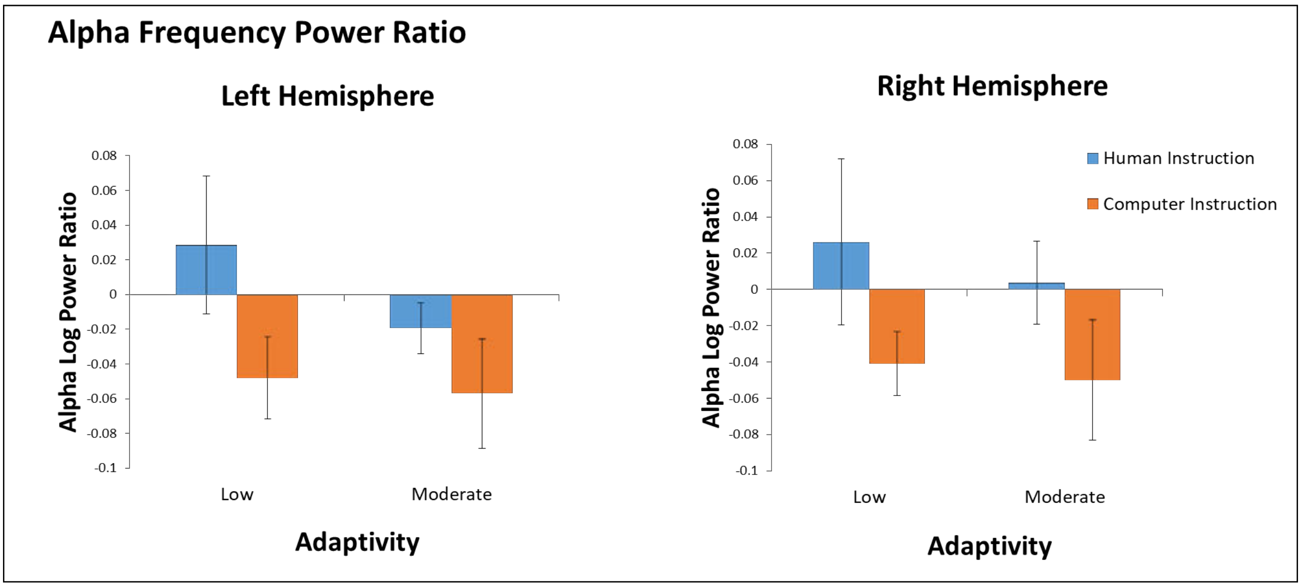
Figure 4.7: Topography of EEG alpha frequency power (8 – 12hz)



Note: Topography of average sensorimotor alpha frequency (8 – 12hz) for the human and computer social instruction conditions at each level of VP adaptivity. The colour scale demonstrates differences in the amount of alpha activity across the scalp. The blue colour shows lower degrees of alpha activity, whereas the red colour reflects higher degrees of alpha activity.

A (2 (hemisphere) x 2 (VP adaptivity) x 2 (social instruction)) x 3 (preference group) ANOVA was conducted on the sensorimotor alpha LPR calculations. As displayed in Figure 4.8, there was no effect of VP adaptivity on relative sensorimotor alpha ratios. However, there was a significant main effect of Social instruction $F(1,29) = 4.73$, $p = .038$, $\eta_p^2 = .140$, with a higher LPR in the human partner condition ($M = .010$, $SD = .02$) than in the computer partner condition ($M = -.049$, $SD = .016$). These results reflect greater relative alpha suppression when participants were told they were synchronising with the computer partner rather than the human partner (where slight mu enhancement was observed). There was no main effect of preference group, nor were there any interactions ($p > .05$).

Figure 4.8: Mean Sensorimotor Alpha Frequency Power Ratio



Note: Sensorimotor alpha frequency Log Power Ratio (LPR) in the left and right hemispheres for the human and computer social instruction conditions at low and moderate levels of VP adaptivity. An LPR greater than 0 represents alpha enhancement (relative to the active control condition), whereas an LPR less than 0 illustrates alpha suppression.

4.5 DISCUSSION

We investigated whether the belief about the intentionality of a rhythmic drumming partner affected synchronisation at three levels of measurement—the level of behaviour, the level of underlying cognitive mechanisms, and the level of the brain. Specifically, we assessed modulations in drumming performance (accuracy and precision), the cognitive mechanisms that support synchronisation performance (temporal adaptation, temporal anticipation, and anticipatory error correction), and alpha oscillations arising from sensorimotor regions of the brain. It was hypothesised that there would be variations across all three levels of measurement, based on whether the drumming partner was portrayed to be an intentional human partner or not. This portrayal was based on both explicit instructions relating to the partner identity, as well as the implicit cue relating to the degree of partner adaptiveness. Additionally, it was also hypothesised that individual differences in partner preference might interact with the effect of partner intentionality.

Firstly, most notable in the present findings is the direct effect of the explicit social instruction on sensorimotor alpha oscillations. This result suggests that at the level of the brain, top-down processes relating to social context can be reflected within the electrical activity of the brain during a rhythmic interpersonal task. Secondly, at the level of the cognitive-motor mechanisms, there was also an effect of VP adaptivity on all three measures, and additionally, there was also an influence of the explicit social instruction on two of the measures—period correction and temporal anticipation. Finally, at the behavioural level, as hypothesised, there were clear effects of the modulations in VP adaptivity with synchronisation performance improving as the VP became more adaptive. However, contrary to our hypotheses, there was no effect of the explicit instructions, nor any interaction between partner preferences and social instruction. Each of these effects will be further discussed below.

4.5.1 Sensorimotor Alpha Suppression

As hypothesised, at the level of the brain, the explicit social instruction modulated activity within the alpha frequency over sensorimotor regions. However, the direction of this effect was in the opposite direction to what was predicted. In line with previous studies that observed mu suppression during joint tasks, we predicted that there would be suppression of alpha activity (relative to the baseline condition) during the human instruction condition. This finding would have supported that sensorimotor alpha suppression (including mu suppression) is a neural correlate of co-representation and motor simulation of a co-actor during rhythmic interpersonal coordination. However, in contrast, our results showed greater degrees of sensorimotor alpha suppression during the computer instruction condition and little to no suppression during the human instruction condition.

On the surface, these results may imply that simulation of the drumming partner was more likely to occur when the partner was perceived to be an unintentional co-actor. However, an alternative explanation, consistent with the findings of Novembre et al. (2016), is that, rather than a direct association with co-representation, sensorimotor alpha suppression may reflect the regulation of the balance between self-other integration and segregation. In a piano duo task, Novembre et al. (2016) demonstrated that sensorimotor alpha suppression was related to higher degrees of self-other integration. That is, when representations of a co-performer's actions are more strongly taken into account and merged with representations of self. In contrast, they found that sensorimotor alpha enhancement reflected greater segregation between representations of self and other, in which case attention is focused internally on the one's own part, and the co-performer's actions have less influence on one's subsequent action timing.

From this perspective, our results suggest that during synchronisation with the VP, people are more likely to focus on the external auditory sequence when it is believed that the partner is a computer. Whereas, with the belief of a human drumming partner, people were more likely to focus more so on their own motor performance. This may be due to an assumption that a human partner is 'like me' and will be able to adapt and respond to my timing (Gallese, 2005). As such, a strategy that recognizes that a human partner can follow and takes into account their adaptive capacity may instead include a focus on making one's own signal more predictable rather than being purely reactive to the external sequence. For example, one may take more of a leadership role with a human partner by maintaining a clear tempo-changing trajectory. This notion is consistent with visual joint action research that shows that people will reduce their movement variability (Vesper et al., 2011) and modify their movement kinematics (Vesper et al., 2013; Vesper & Richardson, 2014) to make their movement timing easier for a co-actor to predict (Colley, Varlet, et al., 2018; Vesper et al., 2017). Thus, during synchronisation with a human partner, a leadership strategy that considers the reciprocal adaptation and anticipation between oneself and the co-actor may be optimal (Konvalinka et al., 2010). However, such a strategy requires more of a focus on the planned timing of self and less attention to the timing of other, and therefore greater self-other segregation is needed and thus lower sensorimotor alpha suppression.

Whereas, when synchronising with an unintentional partner (here, a computer-generated sequence of sounds), it is assumed that it will neither anticipate nor adapt to one's action timing. Therefore, in order to successfully synchronise with an unintentional partner, the onus must be on the self to follow. Thus, when synchronising with an unintentional agent, a follower strategy that more so incorporates the partner's timing into one's own motor plan may be the best approach (as in Novembre et al., 2016). Therefore, the greater sensorimotor alpha suppression observed in the computer condition may reflect greater degrees of self-other integration.

A similar surprising finding was observed by Cross et al. (2012), who, in contrast to previous findings, found greater activity in brain regions associated with the action observation network when people observed robotic-like motion compared to natural human-like motion. Interestingly, this was the case independent of whether the performer was a human or a robot. One proposed interpretation for this effect is that the less familiar robot-like motion led to greater top-down compensatory modulation of the action observation network. This may be due to the higher probability of prediction error between the predicted movement trajectory and the observed movement. This interpretation may also relate to the present findings where prior experience with computers leads to expectations of an unresponsive computer partner; hence there is a greater chance of prediction error when the computer partner is responding in an adaptive way. Thus, consistent with the interpretation of Cross et al. (2012), the current findings suggest that prior experience with a partner leads to expectations and beliefs about the actions of that partner, and these beliefs result in top-down modulations that may influence neural activity during representation of another's actions.

Overall, at the level of the brain, these results provide support for sensorimotor alpha suppression as an index for the regulation between integration and segregation between representations of self and other. Moreover, these findings demonstrate that mere beliefs about social context during rhythmic coordination led to changes in sensorimotor activity within the brain and importantly also provide physiological evidence for the influence of top-down processes on the neural mechanisms involved in rhythmic interpersonal coordination.

4.5.2 Cognitive-Motor mechanisms supporting synchronisation performance.

At the level of the cognitive-motor mechanisms that support synchronisation, there were effects of both the explicit instruction and VP adaptivity; however, these effects were not uniform across the three measures of period correction, temporal anticipation, and anticipatory error correction. In regards to period correction (or how adaptive an individual was toward their drumming partner), although there was a decrease in the amount of period correction that was employed as VP adaptivity increased overall, this effect was modulated by the social instruction. At low levels of adaptivity (i.e., when the VP was correcting for only 10% of the previous asynchrony), participants employed significantly less period correction when told that their drumming partner was a human compared to a computer partner. In other words, participants compensated for the lower level of adaptivity (by increasing the amount of period correction they employed) when told they were synchronising with the computer partner, but not when instructed that the partner was a human.

These results suggest that people modulate the amount of error correction employed depending on how adaptive a synchronisation partner is; however, this is sensitive to beliefs about the type of partner. Perhaps when told that the partner is a human, even though the actual amount of adaptivity was low, participants allowed for the human partner's capacity to employ error correction (rather than the actual amount of adaptivity). Thus, the assumption that a human partner will use commensurate amounts of error correction may lead people to reduce their own amount of error correction, even when the partner is only engaging in low amounts of adaptivity. However, with the computer partner, no such assumption is made, and people will modulate the degree of error correction as needed to ensure successful synchronisation.

In regards to temporal anticipation, similar to the previous studies in this thesis, the overall amount of prediction employed was low, suggesting that participants in the present study predominately favoured a tracking strategy. Nonetheless, there were significant effects of both VP adaptivity and of the social instruction on the relative degree of tracking employed. At higher levels of VP adaptivity, there was less anticipation employed, suggesting that as the VP increased the amount of error correction, participants were more likely to copy the previous interval rather than make an active prediction. This reduction in temporal anticipation reflects that people will reduce the amount of effortful predictive processes when a partner is more adaptive, and synchronisation becomes easier. This modulation suggests efficiency in the use of effortful cognitive resources, with less anticipatory resources employed when not necessary for successful synchronisation.

Interestingly, in contrast to the previous experiments in this thesis, there was also an effect of social instruction on temporal anticipation. The direction of this effect suggests that participants were relatively more likely to employ effortful anticipation when they were told that the partner was a human rather than when a computer. The mere belief of a human partner appears to have led to an increased tendency to actively predict their partner’s next drum stroke, whereas, with the computer partner, a tracking strategy was more likely to be employed. In support of previous findings in joint action research, this may be due to an increased tendency to co-represent and simulate an action partner when they are perceived as an intentional agent (Atmaca et al., 2011; Novembre et al., 2014; Tsai et al., 2008).

This finding in relation to temporal anticipation indicates stronger co-actor simulation in the human partner condition rather than the computer condition. However, as previously discussed, there was greater sensorimotor alpha suppression in the computer condition rather than the human condition. If sensorimotor alpha suppression is a direct correlate of co-representation and simulation, then it would be expected that the direction of these effects would be the same—with greater sensorimotor alpha suppression in the condition with higher amounts of effortful anticipation being employed. Instead, there was greater alpha suppression in the computer condition when there was also a greater tendency to track or follow the partner rather than predict. The inconsistency between these two findings further supports the interpretation that sensorimotor alpha suppression may more so reflect self-other integration rather than co-actor simulation. With the computer partner, a ‘follower’ strategy requires greater integration of the external signal into the motor plan. This interpretation may be tested in future studies by including a leader-follower instruction within the current paradigm to see if explicitly employing a follower role also leads to sensorimotor alpha suppression. Nonetheless, these results invite re-evaluation of the functional significance of sensorimotor alpha power as an indicator of self-other integration, more than simply simulation of one’s partner during joint action.

In relation to anticipatory error correction, like period correction and temporal anticipation, there was also an effect of VP adaptivity. These results suggest that as a drumming partner becomes more adaptive, people are more likely to rely on their own predicted motor plan rather than incorporating their predictions of other into their action timing. One reason for this may be that when the VP introduces higher degrees of error correction and is more reactive to synchrony errors, there may be more deviation away from the original template of the tempo changing sequence. This deviation results in more variation in the sequence timing, which makes temporal prediction more difficult and less likely to be accurate. Thus, in the context of higher partner adaptivity, with the chance of less accuracy in predictions for other, it makes sense to place greater weight on the planned movement timing for self and less weight on the prediction for other when determining the precise timing of the next action. These results correspond to the temporal anticipation results, with less prediction being employed as VP adaptivity increases. It seems that as the degree of effortful prediction decreases, humans are also less likely to incorporate these predictions into their movement timing.

Together, the effect of VP adaptiveness across all three underlying mechanisms reveals that at the level of cognitive-motor rhythmic coordination skills, people are sensitive to changes in how responsive a synchronisation partner is and will modulate the degree to which they implement each of the underlying mechanisms of sensorimotor coordination. Such sensitivity and reactivity towards a partner’s timing highlights that during interpersonal coordination, people will continuously monitor their partner’s level of responsiveness and respond accordingly with alterations to their own basic interpersonal coordination mechanisms to facilitate successful synchronisation. This is consistent with previous studies that show that during joint action, people will modify their own behaviour to take their partner’s abilities into account (Meyer et al., 2016; Richardson et al., 2007; Skewes et al., 2014)

Furthermore, the effect of the explicit social instructions on period correction and temporal anticipation reveals that top-down processes that incorporate contextual cues and social beliefs can modify the extent to which the cognitive mechanisms that support rhythmic interpersonal coordination are employed. The mere belief of a human partner led to an increased tendency to actively predict and a decreased tendency to adapt when the partner was less responsive. Together, these observations suggest that, with the belief of a human partner, there is a greater tendency to adopt a leadership role that also considers the partner's capacity to adapt, as well as a greater tendency to employ simulation of a co-actor to predict their timing accurately. These conclusions are consistent with the premise of greater segregation between representations of self and other with the belief of a human partner, which is in line with the sensorimotor alpha suppression findings.

In conjunction with the above findings, we also assessed how each of the above cognitive-motor mechanisms contributes to synchronisation accuracy and precision. In both measures of synchronisation performance, the combination of all three mechanisms could account for a significant proportion of variance. However, for synchronisation accuracy (absolute asynchrony), period correction was the only unique predictor in the human partner condition, whereas anticipatory error correction emerged as the only unique predictor in the computer partner condition. This result implies that depending on the belief of which partner there was, different strategies were employed to maintain synchronisation accuracy. Modulations in the degree of adaptivity contributed to performance with the belief of a human partner, whereas the extent that predictions of other influenced timing were more important with the belief of a computer partner. This is in line with the argument that people are more likely to integrate self-other predictions when they believe their partner is a computer. In contrast, with synchronisation precision (SD of asynchronies), once shared variance was removed, both period correction and anticipatory error correction emerged as predictors with both the human and computer partners. These results suggest that, regardless of the type of partner, both period correction and anticipatory error correction contribute to the stability of synchronisation. Taking both measures of performance into account, these results indicate that a general reactive rather than predictive strategy was employed.

4.5.3 Synchronisation Performance

At the level of behaviour, as expected, performance (both synchronisation accuracy and precision) improved as the level of VP adaptivity increased. This is in line with the previous studies within this thesis. However, contrary to our prediction, there was no effect of social instruction, and this was unaffected by partner preferences. There was, however, an interaction between adaptivity and partner preferences for synchronisation accuracy, with the rate of improvement as VP adaptivity increased differing between the three preference groups. These results indicate differing degrees of sensitivity to partner adaptivity across the groups. Specifically, participants without a preference for a human or computer partner demonstrated the greatest overall sensitivity to the VP with significant improvement at each successive increase of adaptivity. In contrast, participants with a preference for a human partner showed the greatest sensitivity between low-to-moderate adaptivity (which is most common in humans; Mills et al., 2015), whereas participants with a preference for computers were more responsive to differences between moderate to higher degrees of adaptivity. This suggests that personal preferences may modulate the degree to which changes in partner responsiveness are attended to.

There was no direct effect of partner preference or the social instruction on performance; however, to follow-up the previous findings that showed this effect, participants' attitudes towards computers scores were used to predict relative performance in each of the social instruction conditions. These results showed that those with a greater liking for computers performed better (were more accurate and more precise) when told their drumming partner was a computer. Whereas those who prefer to work with people over computers synchronised better when told that their partner was human. This finding supports the premise that individual differences in personal preferences and attitudes can influence performance when synchronising with different types of partners. Notably, similar to the findings in chapter 2, the direction of this relationship showed better performance with the preferred partner. A striking implication here is that higher-order processes related to social attitudes and beliefs influence basic sensorimotor processes, which adds to the growing evidence that individual's biases can modulate sensorimotor processing during joint tasks (Gutsell & Inzlicht, 2010; Molenberghs et al., 2013).

4.5.4 Individual differences in subjective partner preference.

Across all levels of analysis, contrary to the hypothesis, there were no effects of subjective preferences for which partner was easier to synchronise with. This may be due to the small and somewhat uneven group sizes in this experiment. What is interesting, though, is that similar to the previous experiments in this thesis, there were again differences in the perception of which condition was easiest. As mentioned in previous chapters, as the conditions were identical apart from the verbal instruction about who the partner was, most participants (61.5 %) made a directional post-task choice as to their preferred drumming partner. This replication is further evidence that individuals indeed differ in their perception of task performance, and this may be based on higher-order beliefs (Grigaityte & Iacoboni, 2016; Molenberghs et al., 2013)

The vast majority of previous studies investigating mu suppression have compared mu power relative to a baseline condition where the participant is at rest (e.g. Gutsell & Inzlicht, 2010; Muthukumaraswamy et al., 2004; Naeem et al., 2012a; Oberman et al., 2007; Perry et al., 2011; Pineda & Hecht, 2009). This method was not possible here because of the large drumming movements involved with the task. Comparing alpha power at rest with the drumming conditions would have acted as a confound to the conditions of interest. As such, the easier VP adaptivity condition was chosen as the point of comparison; however, this does not necessarily constitute 'mu suppression' as generally described in the literature. For this reason, we refer to sensorimotor alpha suppression in this study to distinguish our measurement from traditional measures of ‘mu suppression’. Future studies may address this limitation by including auditory-only conditions where participants listen to sounds produced by a human versus a computer partner without the active component. Such a study will also provide further information about whether the functional significance of sensorimotor alpha power relates more so to action simulation or self-other integration and segregation.

In sum, the results of the present study demonstrate that mere beliefs about the intentionality of an interaction partner can modulate the way one synchronises during interpersonal rhythmic coordination. This is evidenced at the level of behavioral performance, the cognitive-motor mechanisms that support synchronisation, and most notably, the level of the brain. This finding provides further evidence that higher-order processes can and do modulate the basic sensorimotor processes involved in joint action. A particularly informative finding is that there was relatively more sensorimotor alpha suppression with the belief of a computer partner rather than a human partner. This suggests that rather than sensorimotor alpha rhythms relating directly to the representation of a co-actor, this frequency may more so reflect a regulatory process that moderates the degree to which representations of other are integrated with representations of self. The measures of the cognitive-motor mechanisms underpinning synchronisation also support this interpretation. There was a greater tendency to actively predict the sequence timing and integrate these predictions with the belief of the unintentional computer partner. Whereas, with the intentional human partner, a leadership strategy focusing on stable, predictive performance rather than reactive performance was observed. Such a strategy requires greater segregation between self and other and, fitting with the findings of Novembre et al. (2016), ties in with the reduction in alpha suppression. Unlike the previous studies of this thesis, the present study did not find evidence that individual differences in preferences modulate the effect of partner intentionality. However, we did find that pre-existing attitudes towards computers could predict whether performance was better with the human or computer partner. Taken together, the findings of the present study highlight the importance of accounting for social context and individual differences in social attitudes when investigating the mechanisms supporting rhythmic interpersonal coordination.

Chapter 5: A Pooled Analysis of Data from Experiments 1 and 3

5.1 INTRODUCTION

The aim of this thesis was to investigate the role of social factors within rhythmic interpersonal coordination. These social factors include extrinsic factors, such as the social context, and intrinsic factors, such as individual differences in social preferences. The social context was manipulated using both implicit and explicit cues as to whether or not a synchronisation partner was an intentional agent. In reality, the partner was always a virtual partner (VP) that implemented various levels of adaptive timing. Throughout all the experiments, there was a reliable effect of the implicit cue relating to how adaptive the partner was. However, there were inconsistent results regarding the explicit cue of the verbal instructions relating to who the partner was. Additionally, in all experiments, any effects of social instruction were moderated by individual differences in partner preferences or social attitudes.

A limitation of the experiments is the small sample size, particularly after dividing the participants into three separate groups based on their subjective preferences. With the small effect size for the social instruction manipulation, the reason for the inconsistent results may be that there was insufficient statistical power to detect any effects. A larger sample will allow closer examination of the effects of the portrayed social context and additionally will aid in better understanding the role of individual differences in preferences and biases. Thus, a pooled analysis was conducted, which included the behavioural data from the two experiments that manipulated the social instruction to imply either a human or computer partner. The two experiments include experiment one—'intentionality of a co-actor' (outlined in chapter 2) and experiment three—'co-actor intentionality and alpha suppression' (outlined in chapter 4). The aim of both experiments was to investigate the role of social context on rhythmic interpersonal coordination using both implicit and explicit cues to indicate the partner's intentionality.

There were many similarities between the two experiments. In both, the VP was used as a synchronisation partner at various levels of adaptivity to implicitly imply a more or less responsive partner. Both experiments included identical low and moderate levels of adaptivity. However, experiment three also included a third, higher level of adaptivity, which is not included in this pooled analysis. The additional third level in experiment three was intentionally presented after the counterbalanced low and moderate adaptivity conditions so it would not act as a confound when comparing the data between the two experiments. Another similarity between the experiments was the use of deception to portray a human synchronisation partner (when in actuality, the VP was always the partner). In both experiments, the participants were verbally instructed at the beginning of each block as to whether they were synchronising with a computer-generated sequence of sounds or if they were synchronising with a fellow participant. Finally, after both experiments, participants were asked which partner was easier to synchronise with— 'the human partner', 'the computer partner', or 'it was the same'—yielding three post-hoc partner preference groups. Finally, in both experiments, the participants were either first-year psychology students who participated for course credit or were volunteers from the university community.

There were some minor differences in the strategies used to portray the social context in each experiment. In experiment one, two participants were tested concurrently. After an initial practice session where the two participants were trained how to drum together, the participants were placed in separate booths, where they were told they would be able to hear the other participant's drum strokes through headphones. In addition, there was a dual-video set-up where participants could see and talk to each other between blocks and were required to solve a joint problem-solving task. In contrast, in experiment three, the co-participant was a confederate who took part in the initial joint practice session and pretended to enter a second booth. Thus, unlike experiment one, there was no further verbal or visual interaction between the participant and their 'partner' once testing began (although the experimenter pretended to have conversations with the 'partner' throughout the experiment to maintain the illusion). However, the most apparent difference was that experiment three was an EEG study and experiment one was not. Thus, experiment three required a much longer setup time, the attachment of electrodes and other equipment, and apart from the drumming movement, all other body movement was restricted.

There were 44 participants in experiment 1 and 30 in experiment 3, bringing the total number of participants used in the pooled analysis to $N = 74$. After dividing the total sample into the three partner preference groups, there were $n = 25$ in the human partner preference group, $n = 25$ in the computer partner preference group, and $n = 24$ in the group who reported no differences in difficulty between the partners.

5.2 RESULTS

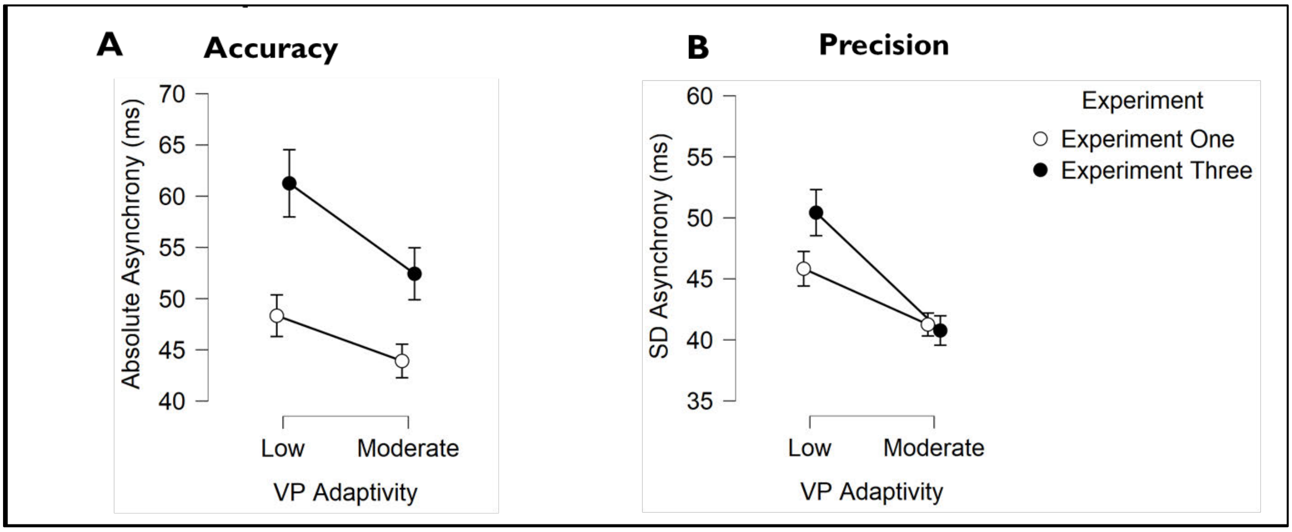
A (2 x 2) x 3 x 2 ANOVA was conducted, with two within-subjects factors, including Social Instruction (human or computer partner) and VP Adaptivity (low or moderate). The between-subjects factors included the Partner Preference grouping (prefer human, prefer computer, no preference), and Experiment, referring to which experiment the data was obtained from (Experiment 1, 'Co-actor Intentionality' or Experiment 3, 'EEG and

Intentionality'). The dependant measures analysed include two measures of synchronisation performance—accuracy (mean absolute asynchrony) and precision (SD asynchrony), and three measures relating to the cognitive-motor mechanisms that underpin synchronisation—period correction, temporal anticipation, and anticipatory error correction.

5.2.1 Between Experiment Effects

There were differences between Experiment 1 and Experiment 3 in both of the measures of synchronisation performance. As shown in Figure 5.1A, there was a main effect of Experiment $F(1,68) = 6.31$, $p = .014$, $\eta_p^2 =.085$, for synchronisation accuracy, with significantly better performance (lower asynchrony) in experiment one (non-transformed M =46.11ms, $SE = 2.83$) compared to experiment 3 (non-transformed M =58.08ms, $SE = 3.51$). For synchronisation precision, there was a VP Adaptivity x Experiment interaction $F(1,68) = 15.38$, $p <.001$, $\eta_p^2 = .184$ (Figure 1B). This interaction was broken down by collapsing the data across the two social instruction conditions and the three preference groups. The simple effects analysis did not survive the Bonferroni correction, and no significant differences were identified. However, as shown in Figure 1B, the general trend suggests that similar to the accuracy results, participants in Experiment 1 were more precise than those in Experiment 3; however, in contrast to synchronisation accuracy, this was only the case during the low adaptivity condition ($p = .085$).

Figure 5.1: Mean Synchronisation Performance Between Experiments



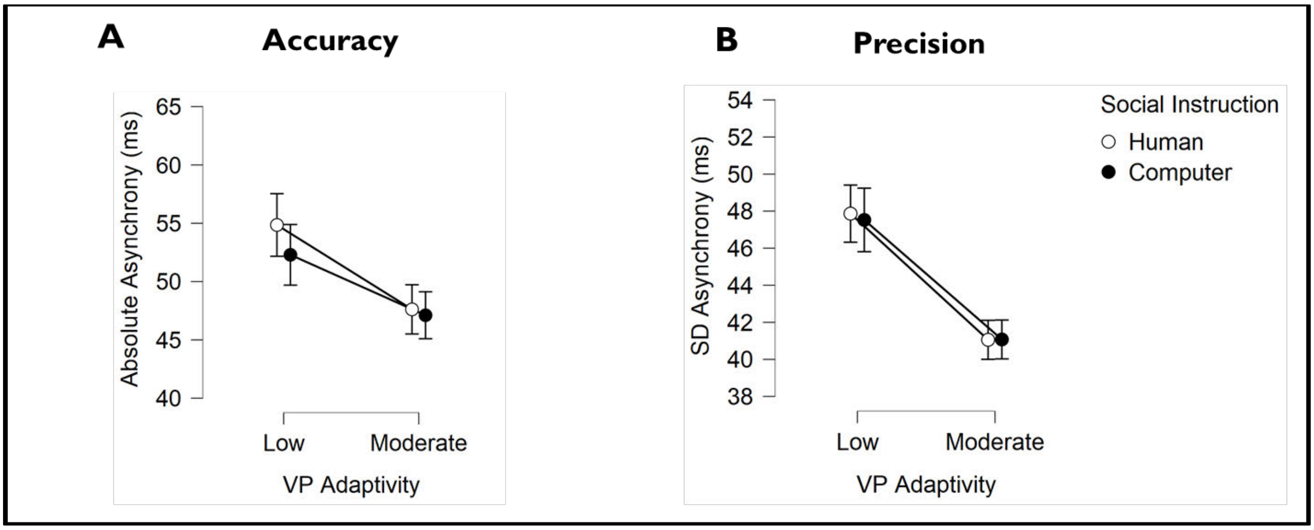
Note: Measures of synchronisation performance for each level of adaptivity between Experiment one and Experiment three. (A) - Synchronisation Accuracy (Mean Absolute Asynchrony, untransformed). (B) - Precision (SD Asynchrony). Error bars represent standard errors of the mean.

These differences in performance may have been due to the EEG setting in Experiment three. The requirement to keep the body still during synchronisation, along with the restrictions imposed by the attachment of the EEG equipment, may have led to the observed detriment in performance. However, with synchronisation precision, the aid of the more adaptive VP appears to have been sufficient to overcome these difficulties, leading to equivalent synchronisation stability during the moderate adaptivity condition. Despite these differences in performance, reassuringly, there was no interaction with the Social Instruction condition or Partner Preference, indicating no significant differences in these effects across the two experiments. There was also no effect of Experiment for any of the parameter estimates of the underlying cognitive-motor mechanisms.

5.2.2 Effects on Synchronisation Performance

As expected, the analysis of synchronisation accuracy (log-transformed absolute asynchrony) revealed a significant main effect of VP Adaptivity (see Figure 5.2A), $F(1,68) = 46.34$, $p < .001$, $\eta_p^2 = .405$, with significantly lower asynchrony (greater accuracy) in the moderately adaptive condition (non-transformed $M = 47.3$ms, $SE = 2.19$) compared to the low adaptivity condition (non-transformed $M = 53.64$ms, $SE = 2.19$). There was no main effect of the Social Instruction, but there was an interaction between Social Instruction and VP Adaptivity $F(1,68) = 4.98$, $p = .03$, $\eta_p^2 = .068$. Simple effects analysis revealed an effect of Social Instruction at low VP adaptivity but not at moderate VP adaptivity. There was significantly lower asynchrony in the computer partner instruction compared to the human partner instruction when the VP was correcting for only 10% of each successive previous asynchrony. This result suggests that the mere belief of synchronising with a computer rather than another person improves synchronisation performance, but only when the VP is being less responsive and not responding like a typical adaptive human partner. This finding that performance was better with the computer partner at low adaptivity may suggest that with the belief of a human partner, participants allowed for the possibility of their partner being more adaptive, even when the partner was actually only slightly adaptive.

Figure 5.2: Mean Synchronisation Performance

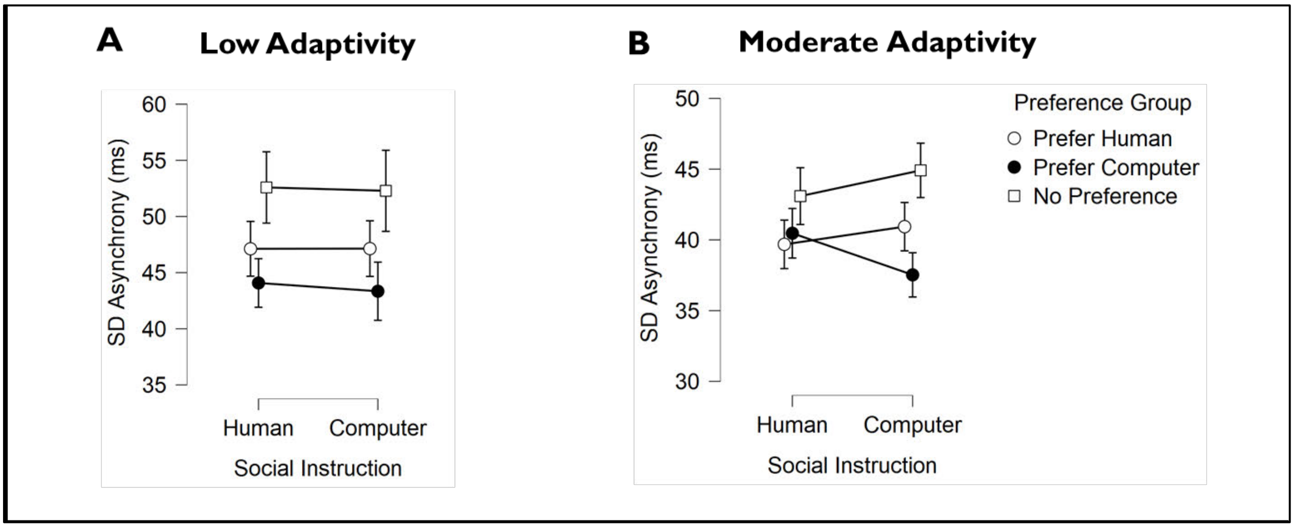


Note: Measures of synchronisation performance for each level of adaptivity (Alpha) between the two Social Instruction conditions. (A) - Synchronisation Accuracy (Mean Absolute Asynchrony, untransformed). (B) - Precision (SD Asynchrony). Error bars represent standard errors of the mean.

The analysis of synchronisation precision (SD Asynchrony) also revealed a significant main effect of VP Adaptivity $F(1,68) = 103.60$, $p < .001$, $\eta_p^2 = .604$ (Figure 5.2B) with participants being more precise (lower SD asynchrony) in the moderately adaptive condition (M =40.77ms, SE = 1.28), compared to the low adaptivity condition (M =47.99ms, SE = 1.28). There were no other main effects, but there were several interactions. There was a 2-way VP Adaptivity x Partner Preference interaction $F(1,68) = 3.18$, $p = .048$, $\eta_p^2 = .085$, however, there was also a 3-way VP Adaptivity x Social Instruction x Partner Preference interaction $F(1,68) = 3.31$, $p = .042$, $\eta_p^2 = .089$. As shown in Figure 5.3, further analysis showed there was a simple effect of Social Instruction during the moderate VP adaptivity condition for the computer preference group only $F(2,68) = 6.651$, $p = .012$. This effect indicates that when the VP was moderately adaptive (Figure 3B), those who found the computer condition easier, were more precise (less variable) when told they were synchronising with a computer partner

(*M* = 38.33, *SE* = 1.82) compared to when told the partner was a human (*M* = 41.04, *SE* = 1.97).

Figure 5.3: The Interaction Between Adaptivity, Social Instruction and Preference Group for Synchronisation Precision.

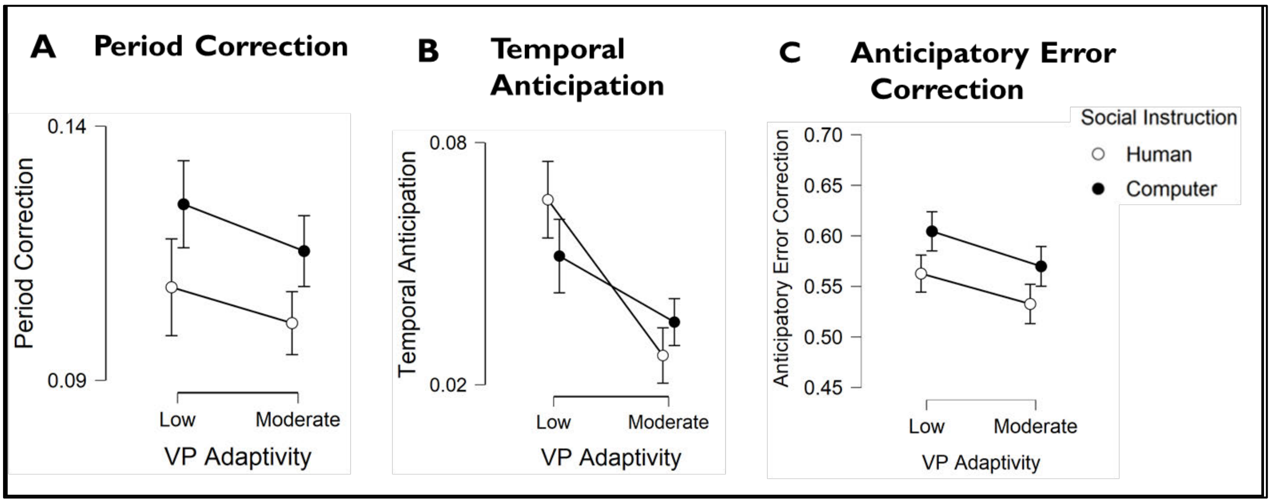


Note: Synchronisation precision (SD Asynchrony) is shown here for each preference group during the two Social Instruction conditions separately for low adaptivity (3A) and moderate adaptivity (3B). Error bars represent standard errors of the mean.

5.2.3 Model-based parameter estimates of the core cognitive-motor mechanisms

The ANOVA on the pooled data relating to period correction found no main effect of VP Adaptivity; however, there was a main effect of Social Instruction $F(1,68) = 4.09$, $p = .047$, $\eta_p^2 = .057$. As shown in Figure 5.4A, this effect indicates that the participants employed less period correction when told that they were synchronising with a human partner (*M* = .010, *SE* = .011) compared to a computer partner (*M* = .013, *SE* = .011). This reduction in the degree of participant adaptivity during the human partner instruction suggests that when told the partner is an intentional human who also has the capacity to be adaptive, people will reduce the degree of their own adaptation. Whereas, in comparison, the belief of a computer partner may not have been perceived to have the capacity, nor the intention to be a responsive and adaptive partner. In addition, this difference in the degree of period correction between social instruction conditions is independent of the actual degree of adaptation being implemented by the synchronisation partner. This finding, again, suggests that the cognitive-motor mechanisms underpinning synchronisation are sensitive to contextual top-down social beliefs. There were no other main effects and no interactions.

Figure 5.4: Mean Parameter Estimates



Note: Model-based parameter estimates calculated using ADAM for each level of adaptivity between the two Social Instruction conditions. A- Period Correction, B- Temporal anticipation, and C- Anticipatory error correction. Error bars represent the standard error of the mean.

The analysis relating to temporal anticipation revealed a significant main effect of VP Adaptivity $F(1,68) = 6.25$, $p = .015$, $\eta_p^2 = .084$ (Figure 5.4B), with more temporal anticipation being employed during the low adaptivity condition ($M = .585$, $SE = .007$), compared to the moderate adaptivity condition ($M = .034$, $SE = .007$). This result suggests that when the VP was more responsive, and synchronisation became easier, participants reduced the amount of effortful prediction they employed. There were no other main effects and no interactions.

In regards to anticipatory error correction, firstly, the ANOVA indicated a main effect of VP Adaptivity $F(1,68) = 29.53$, $p < .001$, $\eta_p^2 =.303$, (Figure 5.4C), with less anticipatory error correction employed in the moderately adaptive condition ($M =.539$, $SE =.017$), compared to the low adaptivity condition ($M =.573$, $SE =.017$). Secondly, there was also a main effect of Social Instruction *F*(1,68) = 4.42, $p = .039$, $\eta_p^2 = .061$, with less anticipatory error correction with the human partner instruction (*M* =.543, *SE* =.018) than the computer partner instruction (*M* =.590, *SE* =.018). These two main effects suggest that participants were less likely to incorporate their prediction of their partner’s next drum stroke timing and relied more so on their own motor plan, when the VP was more responsive compared to less responsive, and when they believed they were synchronising with a human partner compared to a computer partner.

Thirdly, as can be seen in Figure 5.5, for the measure of anticipatory error correction, there was also a main effect of Partner Preference *F*(2,68) = 4.00, $p = .023$, $\eta_p^2 = .105$. Post Hoc tests with a Bonferroni correction revealed that the No preference group overall employed less anticipatory error correction (*M* =.499, *SE* =.029) than either the Human partner preference group (*M* =.596, *SE* =.028) or the Computer partner preference group (*M* =.607, *SE* =.028). This effect indicates that those who subjectively found no difference between the two types of partner in the degree of difficulty to synchronise were less likely to integrate their predictions of other into their motor plan. In other words, those who were neutral in their preferences demonstrated greater self-other segregation and maintained a greater distinction between themselves and their partner, regardless of whom they were told they were synchronising with or how adaptive the VP was.

Figure 5.5: Mean Anticipatory Error Correction for the Partner Preference Groups

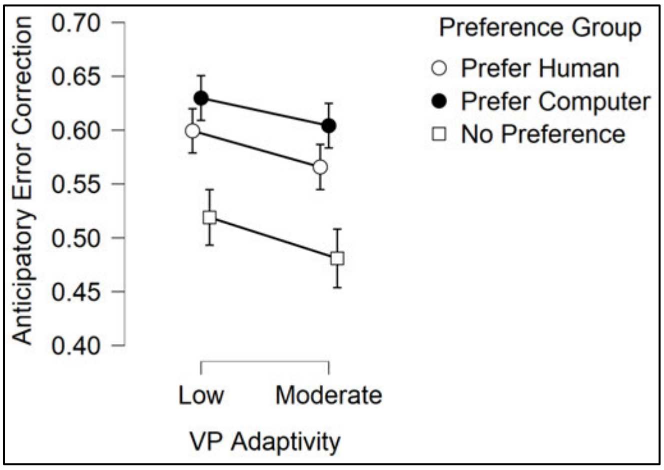


Figure 5.5: Estimates of anticipatory error correction for the three partner preference groups at low and moderate VP adaptivity. Error bars represent standard errors of the mean.

5.3 DISCUSSION

The aim of this pooled analysis was to re-examine the effect of partner intentionality on rhythmic interpersonal coordination with a larger sample than previously used. Of particular interest was the impact of explicit instructions relating to the intentionality of a synchronisation partner and also individual differences in partner preferences. To further investigate the effect of partner intentionality, corresponding data from two experiments with similar designs were combined and analysed. As expected, there were clear effects based on how adaptive the VP was: Synchronisation accuracy and precision were improved when the VP implemented moderate adaptivity compared to low adaptivity. In addition, when the VP was more adaptive, participants employed less temporal anticipation and less anticipatory error correction, suggesting that when a synchronisation partner takes on more of the adaptive load, people will firstly reduce the amount of effortful prediction, and secondly, are less likely to integrate these predictions into their subsequent action timing.

However, of particular interest, in contrast to the previous findings in this thesis, with a larger sample, an effect of social instruction has emerged for period correction and anticipatory error correction. When participants thought they were synchronising with a human, they were less adaptive and less likely to integrate their prediction of other into their subsequent motor plan. There was also an effect of social instruction on synchronisation performance, but only when the VP was implementing only a small amount of adaptivity. At low adaptivity, participants were more accurate when they believed that the partner was a computer compared to a human. This improved performance with the computer instruction at low VP adaptivity suggests that participants may have modulated their behaviour based on their prior experience and beliefs about computers, and when the VP was behaving in a manner closer to what is traditionally expected from a computer, these modulations led to more successful synchronisation. Together these findings suggest that top-down processes such as contextual beliefs modulate both synchronisation performance and the degree to which the cognitive-motor mechanisms that facilitate synchronisation are employed.

Finally, there were effects relating to individual differences in partner preference, showing that, indeed, attitudes and social biases interact with the way higher-order processes modulate rhythmic interpersonal coordination. Firstly, those that perceived the computer partner as the easiest to synchronise with were more precise with the moderately adaptive VP when told that the partner was a computer rather than a human. Secondly, those who found synchronisation was equally as easy with both the computer and human partner employed less anticipatory error correction and were thus less likely to integrate their predications of other. These findings further highlight that higher-order social cognitive processes can influence synchronisation at the level of both performance and in the underlying cognitive mechanisms.

In sum, combining data from two experiments to achieve a larger sample has allowed more in-depth examination of any effects related to beliefs about the intentionality of a synchronisation partner and also individual differences in partner preferences. Firstly, with a larger sample, unlike the previous studies in this thesis, clear modulations in both performance and the underlying mechanisms of synchronisation were observed based on whether the synchronisation partner was believed to be either a human or computer. Secondly, there were also differences in both performance and anticipatory error correction based on the participant's subjective partner preferences. Together these findings indicate that higher-order contextual beliefs about partner intentionality can modulate the way one engages in a joint synchronisation task. However, because this effect is quite small (e.g. η_p^2 between .057 and .068 for the explicit social instruction condition) and is further affected by individual differences in preferences and attitudes, larger sample sizes may be needed to detect these effects. The findings of this pooled analysis will be further discussed in the general discussion chapter (see chapter 6).

Chapter 6: General Discussion

6.1 INTRODUCTION AND OVERVIEW OF AIMS:

This thesis aimed to better understand how social factors influence rhythmic interpersonal coordination. Although much research has investigated people's exceptional capacity to temporally coordinate their movements with each other and the environment, this work has predominately focused on the basic underlying mechanisms of coordination, and there is little evidence concerning how social factors may influence interpersonal rhythmic coordination. To address this gap in the literature at multiple levels, I draw on several psychological perspectives, including social psychology, music psychology, and cognitive neuroscience. More specifically, I considered theoretical perspectives, including information-processing accounts of sensorimotor synchronisation, alongside theories relating to joint action, such as co-representation, self-other integration and segregation, and concepts related to human-robot interaction.

Throughout the thesis, social factors were considered from two perspectives—extrinsic and intrinsic social factors. Extrinsic factors included the social context and perceived characteristics of an interaction partner (e.g. the degree of partner intentionality and responsiveness), and in all experiments, this was investigated by using both explicit and implicit cues to portray an intentional agent as a synchronisation partner. In comparison, intrinsic social factors addressed individual differences in attitudes and social preferences. Of particular interest was how these intrinsic factors modulated the effects of manipulating the extrinsic social context. A reminder of the construction of the research question can be seen in Table 6.1.

Table 6.1: Overview of thesis research questions

Main Research Question	**How do social factors influence rhythmic interpersonal coordination?**
Question 1	How do extrinsic social factors influence rhythmic interpersonal coordination?
	A. How do implicit cues that imply an intentional and responsive synchronisation partner influence coordination?
	B. How do explicit cues that imply an intentional synchronisation partner influence coordination?
	C. Do these implicit and explicit cues interact?
Question 2	How do intrinsic social factors related to individual differences in partner preferences and social attitudes modulate the influence of extrinsic social factors?

To achieve a comprehensive understanding of the effects of each of the different social factors, rhythmic coordination was assessed at three levels of measurement—the level of behavioural performance, the underlying cognitive-motor mechanisms that support synchronisation (Experiments 1-3), and the level of the brain (Experiment 3). At the level of behaviour, coordination performance was assessed in terms of synchronisation accuracy and precision. At the level of the cognitive-motor mechanisms, the ADaptation and Anticipation Model (ADAM) was used to generate estimates of each participant's degree of adaptivity (period correction), temporal anticipation, and anticipatory error correction. Importantly, these parameters provided an approximation of participant's representations of self, of other, and the interplay between these self-other representations. Finally, in experiment 3, the level of the brain was assessed in terms of EEG oscillatory activity within the alpha frequency band (~10 Hz).

Below, I will first discuss how each experiment's findings relate to each research question before explaining how these findings relate to the existing literature and may contribute to our understanding of social processes and interpersonal coordination during joint action. A summary of the results of each experiment can be seen in table 6.2.

6.2 SUMMARY OF FINDINGS – EXTRINSIC SOCIAL FACTORS

6.2.1 Implicit Cues relating to partner intentionality – VP Adaptivity

The effect of extrinsic social factors was investigated by using both implicit and explicit cues to communicate the intentionality of the synchronisation partner. Across all three experiments, the implicit cue of partner intentionality was the degree of adaptivity that was implemented by a computer-controlled virtual drumming partner (VP). The VP consisted of tempo-changing auditory pacing sequences and was programmed to respond to the participant with various degrees of error correction in order to simulate a more or less responsive drumming partner. In experiment 1, low and moderate degrees of adaptivity was employed, while in experiments 2 and 3, a third higher level of adaptivity was added.

Firstly, at the level of behaviour, throughout all three experiments, synchronisation performance improved in terms of both accuracy and precision as the VP became increasingly adaptive. This improvement in performance suggests that when the VP is more adaptive and thus more responsive, people modulate their performance to maximise synchrony. The direction of the modulation indicates that the implicit sense that a co-actor is actively contributing to a synchronisation task results in the modulation of one’s own motor behaviour. Such modulation in performance may occur because synchronisation with a more adaptive partner leads to an underlying sense of a co-actor’s commitment and willingness to cooperate, resulting in greater reciprocal effort being applied to the joint task.

Table 6.2: Overview of the empirical results for all thesis experiments

Measures	**Experiment 1 'Intentionality of Co-actor'**			
Performance	**VP Adaptivity (Low, Moderate)**	**Social Instruction**	**Preference Group**	**Interaction**
Accuracy	✓ Increased accuracy with moderate VP adaptivity	x	x	✓ Adaptivity x Social Instruction x Preference Group. Improved performance in social instruction condition congruent with partner preference at moderate adaptivity
Precision	✓ Increased stability with moderate VP adaptivity	x	x	x
Parameter Estimates				
Period Correction	x	x	x	x
Anticipation	✓ Less anticipation with moderate VP adaptivity	x	x	x
Anticipatory Error Correction	✓ Less anticipatory error correction with moderate VP adaptivity	x	x	✓ Adaptivity x Social Instruction x Preference Group. Less anticipatory error correction in incongruent preference partner at moderate adaptivity
Measures	**Experiment 2 'Robot Interactiveness'**			
Performance	**VP Adaptivity (Low, Moderate, High)**	**Robot Interactivity**	**Preference Group**	**Interaction**
Accuracy	✓ Increased accuracy as VP adaptivity increased	x	✓ MetroBot preference group were more accurate than either SocialBot or No preference groups	✓ Interactivity x preference group The No preference group were more accurate with the socially engaging robot
Precision	✓ Increased stability as VP adaptivity increased	x	✓ MetroBot preference group were more precise than either SocialBot or No preference groups	x

Parameter Estimates				
Period Correction	✓ Less period correction with high VP adaptivity	x	x	x
Anticipation	✓ Less anticipation as VP adaptivity increased	x	x	x
Anticipatory Error Correction	✓ Less anticipatory error correction as VP adaptivity increased	x	✓ MetroBot preference group employed more anticipatory error correction than either SocialBot or No preference groups	✓ Adaptivity x preference group Magnitude differences between the 3 levels of adaptivity
Supplementary Analyses		SocialBot was judged to be more anthropomorphic, animate, and likable than MetroBot.	Post-task preferences, but not pre-existing preferences, predict differences in synchronisation accuracy.	
Measures	**Experiment 3 'Neural Alpha Power'**			
Performance	**VP Adaptivity (Low, Moderate, High)**	**Social Instruction**	**Preference Group**	**Interaction**
Accuracy	✓ Increased accuracy as VP adaptivity increased	x	x	✓ Adaptivity x preference group Magnitude differences between the 3 levels of adaptivity
Precision	✓ Increased stability as VP adaptivity increased	x	x	x
Parameter Estimates				
Period Correction	✓ Less period correction with high VP adaptivity	x	x	✓ Adaptivity x Social Instruction. At low adaptivity, less period correction during the human partner instruction
Anticipation	✓ Less anticipation as VP adaptivity increased	✓ More anticipation employed with the human partner instruction	x	x
Anticipatory Error Correction	✓ Less anticipatory error correction as VP adaptivity increased	x	x	x
Sensorimotor Alpha Power	x	✓ Greater relative alpha power with computer partner instruction	x	x

Supplementary Analyses	Period Correction alone predicts accuracy. Anticipatory error correction is the only unique predictor of Precision.	Attitudes towards computers predict differences between social instruction conditions for synchronisation accuracy and precision		
Measures	**Analysis 4 'Pooled data'**			
Performance	**Adaptivity (.1, .4)**	**Social Instruction**	**Preference Group**	**Interaction**
Accuracy	✓ Increased accuracy with moderate VP adaptivity	**x**	**x**	✓ Adaptivity x Social Instruction. Improved performance in computer partner instruction at low adaptivity only
Precision	✓ Increased stability with moderate VP adaptivity	**x**	**x**	✓ Adaptivity x Social Instruction x Preference Group. Improved performance for the Computer preference group during the computer partner instruction at moderate adaptivity.
Parameter Estimates				
Period Correction	**x**	✓ Less period correction with human partner instruction	**x**	**x**
Anticipation	✓ Less anticipation with moderate VP adaptivity	**x**	**x**	**x**
Anticipatory Error Correction	✓ Less anticipatory error correction with moderate VP adaptivity	✓ Less anticipatory error correction with human partner instruction	✓ The No preference group employed less anticipatory error correction than either the Human or Computer partner preference groups	**x**

The improvement in performance with increased adaptivity corresponds with previous synchronisation studies that use the VP (e.g. Fairhurst et al., 2013; Mills et al., 2015). However, the present results extend previous findings by using tempo-changing sequences rather than isochronous sequences for the base-tempi of the VP. Understanding adaptive processes in the presence of tempo changes is important because many joint rhythmic activities entail rate fluctuations, such as expressive variations in tempo where ensemble musicians speed up or slow down, in addition to mutual adaptation. Experiments 2 and 3 showed that unlike isochronous sequences where a moderate degree of adaptivity is optimal, and performance declines at higher levels of adaptivity, with tempo-changing sequences, performance continues to improve even with higher degrees of adaptivity. The highest level of adaptivity used within this thesis was $\alpha = .7$ (70% correction of the previous asynchrony); thus, the boundaries of this improvement remain to be established.

Secondly, at the level of the cognitive-motor mechanisms, there were modulations within the three experiments based on how adaptive the VP was, and these findings were further validated by the analysis of pooled data from experiments 1 and 3. For period correction (or how adaptive an individual was toward their drumming partner), there was no effect of VP adaptivity on error correction when looking at the low or moderate levels of adaptivity. However, with the inclusion of the higher level of VP adaptivity in experiments 2 and 3, there was a reduction in the amount of period correction employed at this higher level. In regards to temporal anticipation, across all experiments, there was less anticipation employed as VP adaptivity increased, indicating that as the VP increased the amount of error correction, participants were more likely to copy the VP's previous interval rather than make an active prediction. Together these findings suggest that when there is implicit information about co-actor intentionality, the contribution of the partner is recognised, and an individual may opt to rely more so on the more responsive partner to contribute to the joint performance. In other words, people will reduce the amount of effortful predictive and adaptive processes when a partner is more adaptive, and synchronisation becomes easier. This reduction in effortful prediction and adaptation may reflect efficiency in the number of cognitive resources employed when not needed for successful synchronisation.

Likewise, the estimates of anticipatory error correction (where the outcome of one's prediction of other's timing is compared to the motor plan for one's own subsequent movement) also declined as adaptivity increased across all experiments. In other words, participants corrected for a smaller proportion of the difference between their prediction of other (temporal anticipation) and their estimate for self (error correction). These results suggest that as a drumming partner becomes more adaptive, people are more likely to rely on their own predicted motor plan rather than incorporating their predictions of other into their action timing.

There are several possible interpretations of this tendency to favour one's own motor plan rather than integrate the predictions of the partners timing during the high adaptivity condition. Firstly, with the implicit cue of a responsive intentional partner, it may be sensed that the co-actor is capable of taking a follower role. Perhaps participants are more inclined to allow the balance of leading and following to shift between themselves and their partner when their partner is more responsive, requiring less active anticipatory error correction. Previous studies (e.g. Schmidt et al., 1994) have found that joint coordination is optimal when there is a leader and a follower rather than two leaders or two followers. In line with such findings, the current results suggest that when a partner is more responsive, it may be demonstrative of a more 'follower-like' tendency of the partner. In which instance, people may take on more of a leadership role to enhance synchronisation.

Secondly, it may be that when the VP introduces higher degrees of error correction and is more reactive to synchrony errors, there may be more deviation away from the original template of the tempo changing sequence. This deviation results in more variation in the sequence timing, which makes temporal prediction more difficult and less likely to be accurate (Harry & Keller, 2019). Thus, in the context of higher partner adaptivity, with the chance of less accuracy in predictions for other, it may be more useful to place greater weight on the planned movement timing for self and less weight on the prediction for other when determining the precise timing of the next action. These results correspond to the temporal anticipation results, with less prediction being employed as VP adaptivity increases. Thus, when there is less active anticipation, people are also less likely to incorporate these predictions into their movement timing.

Indeed, simulations conducted by Harry and Keller (2019) showed that when two interacting agents have different tempo-changing goals (one agent has a template containing tempo-changes and the other has a stable isochronous template), optimal synchronisation occurs when the agent with the tempo-changing template abandons their template and prioritises synchronisation. In other words, this agent takes on a follower role, leading to a reduction in the magnitude of tempo changes in the sequence; hence the sequence becomes steadier. However, if the goal is to maintain the tempo-changing sequence as well as to synchronise, in the face of a more variable partner (i.e. the higher adaptivity of the VP), prioritising one’s own motor plan not only maintains the tempo-changes but also allows for the partner’s capacity to follow. That is, when a partner is demonstrating higher degrees of adaptive timing, one can implement more leadership by maintaining the timing sequence with some confidence that synchrony will still be maintained. This situation is analogous to playing a musical duet with an accompanist who is being highly responsive, allowing one to instigate expressive tempo changes and trust that the partner will follow.

Interestingly, the changes observed at the level of performance and the cognitive-motor mechanisms when VP adaptivity was modulated were not reflected in changes in electrical activity recorded over sensorimotor regions of the brain in experiment 3. There were no differences in the degree of sensorimotor EEG alpha power between low and moderate VP adaptivity (both relative to the high adaptivity condition). This result may simply reflect that activity within the alpha frequency band over sensorimotor regions is not related to monitoring implicit information about how responsive a synchronisation partner is. Being that there was an effect of the explicit cue (which is discussed in more detail in the next section), this finding suggests that sensorimotor alpha activity is more so related to higher-order explicit knowledge rather than bottom-up sensory information.

Together, the effect of VP adaptiveness across performance and all three underlying cognitive-motor rhythmic coordination skills demonstrates that people are sensitive to changes in how responsive a synchronisation partner is and will modulate the degree to which they implement each of the underlying mechanisms of sensorimotor coordination. This modulation in the mechanisms in response to changes in partner adaptivity suggests that during interpersonal coordination, people continuously monitor their partner’s level of responsiveness and respond accordingly with alterations to their own basic interpersonal coordination mechanisms to facilitate successful synchronisation. This finding is consistent with previous studies that show that during joint action, people modify their own behaviour to take their partner’s abilities into account (e.g. Meyer et al., 2016; Richardson et al., 2007; Skewes et al., 2014). Overall, these results suggest that implicit cues that imply a more intentional partner, even at the level of changes to micro timing in the tens of millisecond range, are sufficient to elicit changes in the way one engages in rhythmic interpersonal coordination tasks. This interpretation may be extended to imply that during joint tasks, people are sensitive to informational cues about their partner, even if the information is incredibly subtle and not explicitly communicated.

6.2.2 Explicit Cues relating to partner intentionality – Social Context

Explicit cues about the joint context and the intentionality of the partner were investigated in two ways within this thesis. In experiments 1 and 3, the explicit cue was the presence of a co-actor (either another participant- experiment 1, or a confederate- experiment 3), with the addition of a direct verbal instruction to synchronise with either the human partner or a computer-generated sequence of sounds. However, despite the verbal instructions, the drumming partner in all conditions was the VP. Experiment 2 approached the explicit cue of social context somewhat differently. Instead of the belief of an intentional human partner, a humanoid robot was used with two levels of social interactiveness. Here, the robot was portrayed as the drumming partner with two different versions of 'social software'— one that employed explicit communicative cues (speech, eye gaze, and body movements) intended to encourage social engagement and one that did not.

The findings in regards to the explicit social instruction were mixed across the three experiments, which is similar to the findings of previous literature where the findings related to the belief of an intentional partner have been inconsistent (Stenzel et al., 2014; Tsai et al., 2008). A direct effect on behavioural performance was not found, which suggests that independent of explicit beliefs as to whom the interaction partner was (human or computer), performance was similar in terms of synchronisation accuracy and stability. However, there were several interactions between the social instruction and VP adaptivity and the subjective partner preferences collected at the end of each testing session. These interactions indicate that although the explicit instruction in and of itself did not impact synchronisation performance, there were effects that were dependant on these other factors.

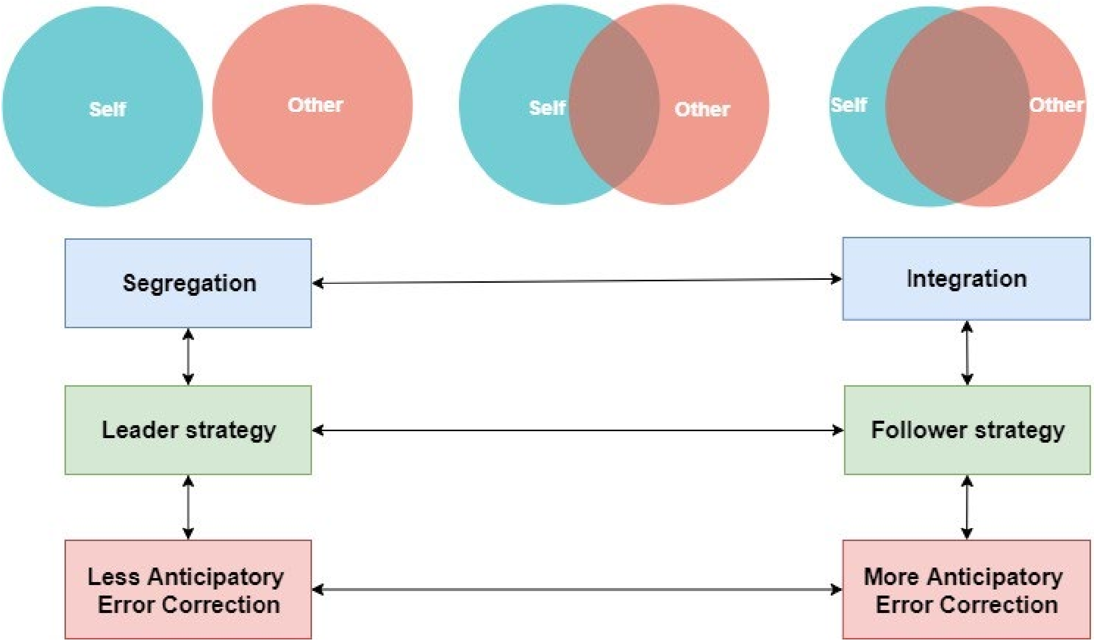
The role of individual differences in partner preferences will be discussed in the following section. However, in regards to VP adaptivity, an interaction with the social instruction was found for synchronisation accuracy in the pooled analysis that combined data from experiments 1 and 3 and hence benefitted from a larger sample size. This effect showed that, at the low level of VP adaptivity (as opposed to moderate adaptivity), participants were more accurate when told that the partner was a computer rather than a human. In other words, the mere belief of synchronising with a computer rather than another person improved accuracy, but only when the VP was correcting for a small proportion (10%) of each successive previous asynchrony. The improvement in performance may be because the low adaptivity condition is more congruent with assumptions about how a computer partner would not be responsive, and participants accounted for this lower level of adaptivity within their own performance by increasing their own degree of adaptivity. Correspondingly, when told that the partner was a human, but the VP was only slightly responsive and not behaving like a typical adaptive human partner, participants may have allowed for the potential of the human partner to be more adaptive, even though this was not actually the case. This interpretation is supported by the findings in regards to period correction, which is discussed in more detail below.

In regards to the underlying cognitive-motor mechanisms of synchronisation, there were some effects of the explicit social instruction; however, these effects were not consistent across the experiments. Firstly, a direct effect for temporal anticipation was observed in experiment 3, where it was found that participants employed more anticipation when told their partner was a human. Here, it appears that the belief of a human partner may have led to an increased tendency to actively predict their partner's next drum stroke, whereas, with the computer partner, a tracking strategy was more likely to be employed. This interpretation relates to previous findings in joint action research, where an increased tendency to co-represent and simulate an action partner has been observed when the partner is perceived as an intentional agent (Atmaca et al., 2011; Novembre et al., 2014; Tsai et al., 2008).

Secondly, it was also found that participants employed less period correction with the belief of a human partner in experiment 3, but only during the low VP adaptivity condition. This effect was also observed with the larger data sample in the pooled analysis. Again, here there was less period correction with the belief of a human partner; however, unlike experiment 3, this reduction was consistent across both VP adaptivity levels. These findings suggest that people may reduce their degree of adaptivity to accommodate their human partner's capacity to also be adaptive, compared to when synchronising with the belief of an unresponsive computer. In general terms, joint synchronisation performance is optimal when interaction partners each implement symmetrical moderate degrees of adaptivity, in other words, when interaction partners are mutually adapting to each other (Elliott et al., 2016; Harry & Keller, 2019; Repp & Keller, 2004, 2008; Repp & Su, 2013). However, optimal performance can also be achieved when the balance of adaptivity shifts between the two partners, for example, as occurs during leader-follower situations where the follower will be more adaptive and the leader is less so (Fairhurst et al., 2014; Konvalinka et al., 2010). The current findings show that beliefs about the nature of an interaction partner can also generate a shift in the amount of adaptivity employed, perhaps to achieve an optimal weighting of adaptivity. Here, with the human partner, people constrained their degree of adaptivity to allow for the partner's potential contribution, whereas with the computer partner, higher adaptivity is used because it is believed that a computer will not be mutually adaptive.

Thirdly, in the pooled analysis, it was found that there was also less anticipatory error correction employed with the portrayal of a human partner, suggesting that people may be less likely to integrate their prediction of their partner's timing into their motor plan with the belief of a human partner. This result is consistent with a synchronisation strategy that incorporates both leader and follower tendencies (Fairhurst et al., 2014). Where, in addition to synchronising, one is also aiming to maintain their own planned timing in order to present a more predictable signal (Vesper et al., 2013), which requires a greater distinction between self and other to allow one's own motor plan to be prioritised. A human partner may be perceived as having the capacity to contribute toward successful synchronisation and thus the capacity to follow. Therefore, with the belief of a human partner, the balance between leading and following may shift between the two partners (Fairhurst et al., 2014; Goebl & Palmer, 2009; Konvalinka et al., 2010). In contrast, with the belief of a computer partner that is thought to have no such capacity to contribute (Lorenz et al., 2016), a follower rather than a leader strategy may more so be employed, requiring more weight being placed on the prediction of the partner's timing, thus greater self-other integration as shown in figure 6.1 (Novembre et al., 2016).

Figure 6.1: Self-Other Integration and Segregation



Note: Schematic of how the different degrees of self-other integration and segregation relate to changes in leader and follower strategies during synchronisation as indexed by anticipatory error correction.

In summary, in regards to the cognitive-motor mechanisms underpinning synchronisation, the instruction that a synchronisation partner was human rather than a computer (sometimes) led to people being more likely to make an effortful prediction about their partner's timing (Experiment 3); yet less likely to use adaptive timing (Experiment 3 and pooled analysis); and less likely to integrate their prediction of other into their subsequent motor plan (pooled analysis). Together, these findings suggest that the mere belief of an intentional partner can lead to people accommodating for their partner's ability to contribute toward the success of the synchronisation task. However, this interpretation must be made with caution, because as discussed, these effects were not consistently found across the experiments. There may be several reasons for this inconsistency. Firstly, there is a relatively small effect size for each of these significant findings (e.g. η_p^2 between .057 and .250); thus, the sample sizes may not have been sufficient to detect an effect of the social instruction. This small effect size is then further compounded by the impact of individual differences in preferences which will be further discussed later.

Finally, the most notable finding related to the explicit social instruction was the clear effect at the level of EEG oscillatory activity over sensorimotor regions of the brain that was observed in experiment 3. Sensorimotor alpha power was reduced with the instruction of a computer partner compared to a human partner, indicating greater alpha suppression with the computer partner. Previous literature has associated modulations in alpha suppression in sensorimotor regions as a neural correlate of co-representation and motor simulation (e.g. Hari, 2006; Hari & Salmelin, 1997; Kourtis et al., 2010; Naeem et al., 2012b; Tognoli et al., 2007), but the present findings do not directly support this idea. In light of this theory, one would expect greater co-actor simulation and representation with the belief of a human partner and thus greater sensorimotor alpha suppression. Whereas these results instead indicated more alpha suppression with the computer partner.

An explanation for this finding may be that rather than sensorimotor alpha suppression relating to co-representation, alpha suppression may more so reflect the degree of self-other integration and segregation during a joint task. In line with this interpretation, Novembre et al. (2016) demonstrated that sensorimotor alpha suppression is related to greater integration between one's own motor plan and simulation of a partner's motor activity. From this perspective, the increase in alpha suppression during the computer partner condition may suggest greater self-other integration with the belief of a computer partner rather than the human. Such integration is consistent with a follower strategy that more so incorporates the partner's timing into one's motor plan, which is a reasonable strategy to use when synchronising with an unintentional partner, who is assumed not to have the capacity to adapt and respond.

Together, these findings imply that top-down processes such as contextual beliefs can modulate synchronisation performance and the degree to which the cognitive-motor mechanisms that facilitate synchronisation are employed. Furthermore, these top-down processes are clearly reflected within sensorimotor oscillatory brain activity. Additionally, the difference in results relating to implicit and explicit cues across all three experiments demonstrates not only the importance of implicit behavioural cues during a joint task but also the dissociation between implicit and explicit cues as to partner intentionality. It appears that in the context of interpersonal synchronisation, implicit cues are more influential than explicit cues at the level of behavioural performance and the cognitive-motor mechanisms. In contrast, explicit cues are more so reflected at the level of sensorimotor alpha activity than implicit cues. Related findings at the level of brain activity were demonstrated by Rolison et al. (2020), who found that the physical presence of another person was sufficient to modulate alpha oscillations over central-parietal regions. However, in the absence of an explicit instruction to interact, the spatial orientation of the person had no further effect. This finding also suggests that sensorimotor alpha activity may be modulated by explicit information about social context but is not affected by more granular levels of information. Several questions arise here; for instance, it will be important to determine if this pattern will hold for people with atypical social cognitive function, for instance, autism spectrum disorders (Dumas et al., 2014; Perkins et al., 2010). Additionally, the impact of implicit social cues during interpersonal coordination may be reflected in activity in other neural frequency bands such as the theta or beta bands (Dumas et al., 2010; Müller et al., 2013; Sänger et al., 2012), or indeed within other brain regions, such as pre-frontal regions (Yun et al., 2012). These questions present a fruitful area for future research and will be informative for understanding the nuances of the workings of the social brain.

A noteworthy issue particularly related to the explicit cue of social instruction was the inconsistent effect across experiments, predominantly concerning the cognitive-motor mechanisms that facilitate synchronisation. There may be a number of reasons for this inconsistency. Firstly, as previously mentioned, there is a relatively small effect size with both behavioural performance and the cognitive-motor mechanisms; thus, the sample sizes may not have been sufficient to detect an effect of the explicit social cue. This small effect size is also compounded by the impact of individual differences in preferences. Once partner preferences were taken into account, a more detailed picture emerged, highlighting how individual differences in attitudes and beliefs have an influential role in whether or not the social context affects rhythmic interpersonal coordination. Taking this influence into account will require samples large enough to detect differences in effects that are modulated by the diverse nature of higher-order processes such as beliefs and attitudes. I will discuss this modulating role of individual differences in more detail here.

6.3 SUMMARY OF FINDINGS – INTRINSIC SOCIAL FACTORS

There are many factors relating to individual differences in intrinsic social factors that may influence how one approaches an interpersonal coordination task, for example, differences in social-cognitive style, personality, attitudes and beliefs, and personal preferences, to name but a few (Gazzola et al., 2006; Novembre et al., 2012; Novembre et al., 2019; Varlet et al., 2014). Within this thesis, the main focus was on individuals' subjective judgements about which synchronisation partner was easier to synchronise with as a potentially modulating factor. The first point to note here is that participants consistently had different views as to which apparent partner was preferred, and the spread of the choices between 'prefer human', 'prefer computer' and 'no preference' was somewhat even throughout all studies. Secondly, across the three experiments, these preference choices modulated many of the effects of both VP adaptivity and the social instruction at the level of both behaviour and the cognitive-motor mechanisms; however, the nature of this modulation was not consistent across the three experiments highlighting the complexity of investigating individual differences.

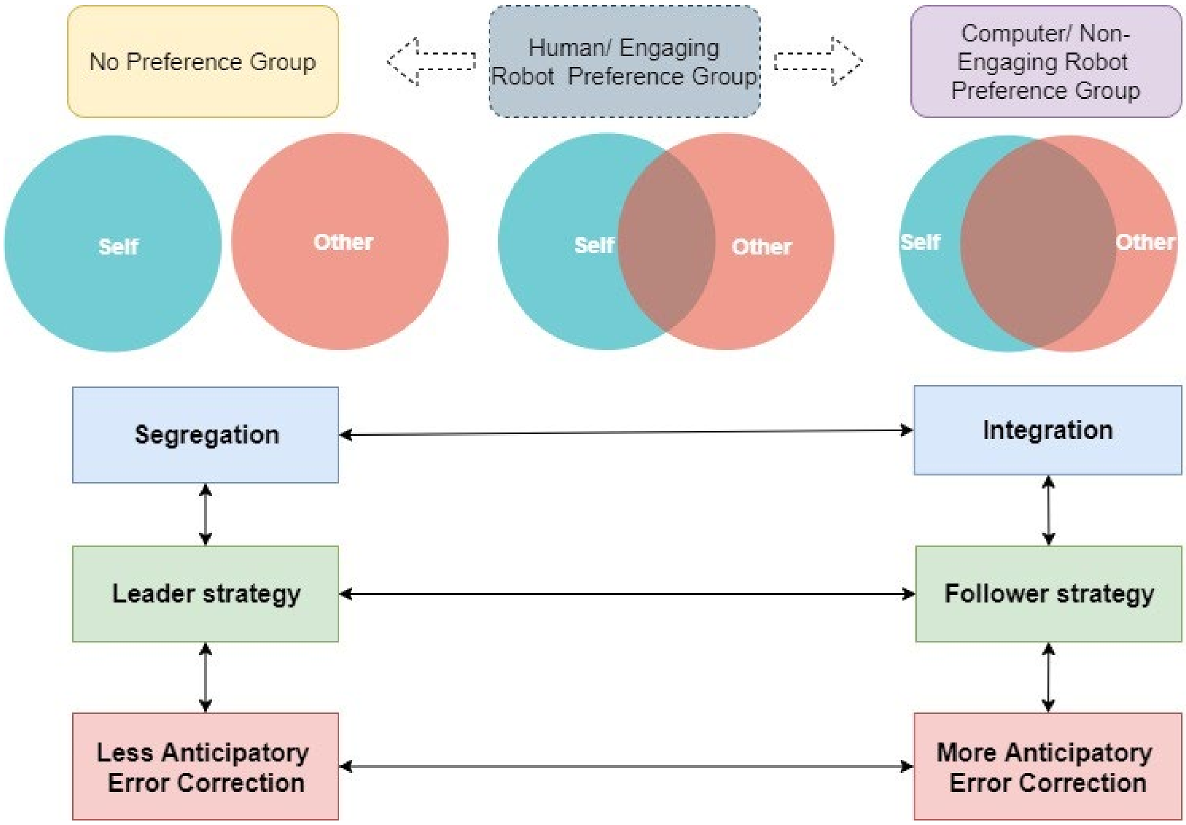
At the level of behavioural performance, an unexpected finding emerged in the robot experiment (experiment 2). Here, instead of merely modulating the effect of robot interactivity or VP adaptivity, there were differences in performance purely based on differences in the choice of the preferred robot. Those who chose the unengaging robot as the easiest robot to synchronise with were more accurate and more precise than those who preferred the socially engaging robot or those who had no preference. This finding suggests that partner preferences may be somewhat driven by synchronisation skill because those who were better at synchronising were more likely to choose the unengaging robot as their preferred partner—this is despite the engaging social robot being rated overall as more anthropomorphic, animate, and likable. Perhaps, those who are good at synchronisation tasks prefer to focus more so on the task at hand, and social engagement may be viewed as redundant or even a distraction in this context. Tay et al. (2014) also found greater acceptance of a social robot when the robot displayed non-verbal cues that portrayed a match in personality to the individual participant. Thus, those who were better at synchronisation may have been more focused on the task itself rather than the social interaction, and perceived the unengaging robot as 'matching' their focus. This finding was not replicated in the other experiments; however, neither of the other experiments specifically addressed social engagement.

Further differences were observed between the three preference groups in the way that the implicit and explicit partner cues affected performance. In experiment 1, the influence of VP adaptivity and social instruction differed depending on which partner was preferred. Generally, performance was more likely to improve with the moderately adaptive VP when the social instruction matched the partner preference. This finding reflects that the improvement in performance that is usually observed at moderate levels of adaptivity, did not necessarily occur when participants were told they were synchronising with the partner incongruent with their preferred partner. In other words, people accommodated the increased adaptivity of the VP, but only when synchronising with the partner they felt was the easiest to synchronise with. Partial validation for this finding emerged from the pooled analysis of experiments 1 and 3. This analysis showed that those who perceived the computer partner as the easiest to synchronise with were more precise with the moderately adaptive VP, but only when told that the partner was a computer rather than a human.

A related finding in the robot experiment also demonstrated modulation of the effects of extrinsic social factors based on the choice of preferred partner. Here, there was an effect of robot interactivity on performance, but only for the group who reported no preference for either robot. These people were more accurate with the socially engaging robot compared to the unengaging robot, an effect that did not occur with the two groups who preferred one robot or the other. This result suggests that the degree of social engagement with a partner can influence how well one synchronises, but this is more likely to occur for those who are neutral in the perceived difficulty of synchronising with the two types of partner. Together these differences in effects based on partner preferences highlight that an individual's subjective judgement of which type of partner is easier to synchronise with relates to differences in the way people approach and behave within a joint task. Previous research has demonstrated that implicit and explicit biases influence many aspects of social processing, including, but not limited to, perceptual judgements (Molenberghs et al., 2013) and co-actor action simulation and co-representation (Gutsell & Inzlicht, 2010; Müller, Brass, et al., 2011).

Differences at the level of the cognitive-motor mechanisms were also observed between the preference groups, specifically within anticipatory error correction. Firstly, in the robot experiment, those who chose the unengaging robot as their preferred partner also engaged in more anticipatory error correction overall than the other two groups. In other words, these people were more likely to incorporate their predictions of the robot's timing into their motor plan, which is indicative of greater integration between their representations of self and other, and consistent with a strategy that favours following rather than leading. It seems that people who are more inclined to use a follower strategy were more also more likely to prefer synchronising with the unengaging robot. It may be that the less engaging and interactive robot is perceived as a 'better fit' for people with a greater tendency to follow who may not see a social connection as essential (or even desirable) to enhance interpersonal rhythmic coordination (see Figure 6.2). This presents an interesting area for future research for those with social deficits, for instance, Autism spectrum disorders.

Figure 6.2: Individual Differences in Partner Preference and Self-Other Integration and Segregation



Note: Individual differences in subjective partner preference are associated with anticipatory error correction, suggesting that social preferences may relate to differences in the degree of self-other integration and segregation. Those who had no preference for either partner appear to have greater self-other segregation, whereas those who preferred the computer/unengaging robot showed greater self-other integration—particularly with the computer partner. In contrast, the human preference group demonstrated self-other integration only when told the partner was a human, potentially suggesting greater flexibility in shifting between self-other integration and segregation.

The modulation of individual differences in preferences was further validated in the pooled analysis of experiments 1 and 3. Here, unlike the computer preference group, those with no specific partner preference employed less anticipatory error correction and thus were less likely to integrate their predictions of other and focused more so on their own motor plan (Figure 6.2). This result reflects greater self-other segregation for those who did not perceive differences in difficulty to synchronise between the human and computer partner. In other words, those who maintained a greater distinction between themselves and their partner, regardless of whom they were told they were synchronising with or how adaptive the VP was, were more likely to be neutral in their preferences. Perhaps, focusing more so on representations of oneself to generate a motor plan results in less attention being paid to ‘other’ (see Novembre et al., 2016), and thus, one is less likely to detect or infer differences in difficulty between the different partner types.

Also, in regards to anticipatory error correction, in addition to the overall differences between the groups, in experiment 1, partner preferences modulated the interaction between implicit and explicit partner cues. Here, participants engaged in more anticipatory error correction when the VP was moderately adaptive, but only during the social instruction that was congruent with their preferred partner. This result suggests that when the VP was moderately adaptive, participants were more likely to integrate their prediction of their partner’s timing into their own planned next movement when instructed that they were synchronising with their preferred partner. This finding that people are more likely to integrate representations of self and other with a preferred partner relates to previous findings that show biases in co-representation and perceptual processes between in-group and out-group members (e.g. Gutsell & Inzlicht, 2010; Molenberghs et al., 2013)

Overall, these findings indicate that beliefs about the intentionality of a synchronisation partner influence interpersonal rhythmic coordination in a manner that is modulated by preferences for interacting with intentional or unintentional agents. Although, it is hard to draw conclusive inferences about the precise nature of how partner preferences influence synchronisation based on the findings of this thesis. However, the general trend seems to suggest that those who do not perceive differences in partner difficulty are less likely to integrate their representation of their partner and less likely to show differences in performance based on an instruction relating to partner intentionality. On the other hand, this same group had improved performance when the partner exhibited socially engaging behaviours, which may suggest that for those who are less likely to integrate, some encouragement to form a social connection and engage with an interaction partner may be beneficial.

In contrast, those who do have a preference for one partner or another are more likely to integrate representations of their preferred partner and, in turn, perform better with that partner. This was even more so pronounced for those who preferred the computer partner or the unengaging robot. These individuals, in particular, consistently showed greater self-other integration with the computer partner and, subsequently, better performance. Together, these findings suggest that individual differences in social preferences play an important role in understanding how people perform in joint tasks and the degree to which people incorporate their co-representations. Rather than a general rule that people are more likely to co-represent with intentional human partners as was initially hypothesised by this thesis, perhaps those who do not enjoy social interaction, or prefer to work with non-interactive partners, find it easier to integrate their self-other representations when the partner is assumed to be less intentional and less engaging. Nevertheless, these findings clearly show that, indeed, attitudes and social biases interact with the way higher-order processes modulate rhythmic interpersonal coordination, highlighting the importance of considering individual differences in social preferences when investigating behaviour in social contexts.

6.4 LIMITATIONS

An important caveat to consider when interpreting the influence of partner preferences throughout this thesis, particularly when inferring a connection to innate attitudes and biases, is that the above findings all emerged from post-task judgements relating to which partner was easier to synchronise with. This presents an interesting issue about whether the preferences relate to pre-existing biases or if performance in the task drove the selection. In other words, what caused the preferences? For instance, was it that those who generally prefer working with humans perceived the human partner condition as easier? Or was it that the experience itself led to the emergence of the preference?—A ‘chicken-or-the-egg’ question. Previous findings suggest that better interpersonal synchronisation leads to increased liking and affiliation (e.g. Hove & Risen, 2009), suggesting the latter explanation. However, in the context of the current thesis, the objective performance of the virtual partner was the same in both social instruction conditions, which leaves the question as to why people performed differently and developed such different subjective views of which ‘partner’ was easiest. Additionally, although performance sometimes improved with the preferred partner, this was not consistently the case, demonstrating that preferences were not solely formed based on better synchronisation.

In an attempt to answer the question of the direction of preference causality, in experiments 2 and 3, I also gathered data on pre-existing attitudes and preferences before the drumming task was completed. The results here are inconclusive. In experiment 2, participants were asked beforehand whether they generally prefer working with humans or computers, and it was found that post-task preferences rather than pre-existing attitudes were more predictive of differences in performance. However, in experiment 3, the attitudes towards computers questionnaire was administered prior to the drumming task, and it was found that attitudes towards computers were predictive of differences in performance between the different partners. This difference in findings may be due to the different nature of the social manipulation between these experiments or that the two measures are in themselves different (one being a categorical forced-choice question and the other a more nuanced questionnaire), and they may tap into different aspects of pre-existing attitudes and preferences. The attitudes towards computers questionnaire was not administered in experiments 1 and 2, and it is unknown what would have been found in these contexts, presenting an additional limitation toward clarifying the origins of partner preferences. Thus, the question remains as to whether it is aspects of the encounter, or pre-existing attitudes, that are more influential in modulating performance in a joint task and is another fruitful area for further research.

Another limitation is the assumption that the partner that was easiest to synchronise with was the preferred partner. Within this thesis, the label of ‘preferred partner’ was operationally defined to reflect this assumption; however, whether ‘easiest’ and ‘preferred’ are equivalent in terms of how participants viewed their partner is unknown. Many other potential characteristics may relate to the classification of a ‘preferred partner (for instance, liking, trust, or respect). This issue may be further investigated in future studies by asking more detailed and nuanced questions about partner preferences, such as “Which partner do you like better?” or “Which partner would you choose for a future coordination task?”. Although the theoretical equivalence between ‘partner preference’ and ‘easiest to synchronise with’ was not tested in this thesis, this is an important consideration, and further studies are needed to clarify what characteristics encompass the construct of ‘preference’.

An additional limitation across the experiments in this thesis did not consider the distinction between computers and robots in the context of interaction partners. In experiments 1 and 2, the non-interactive partner was portrayed as a computer, whereas in experiment 2, it was a non-interactive robot. While a robot and a computer are both machines, there are notable differences between the two; for instance, a robot has additional sensory and motor functions, which depicts an increased capacity to interact with the environment. Additionally, the robot used in this thesis appeared similar in form to a human, thus further encouraging the notion of a more interactive machine than a computer. Such embodiment that is portrayed by social robots compared to computers is an important consideration when considering human-machine interaction (see Henschel et al., 2020), and thus, the non-interactive conditions across experiments should not be considered equivalent. Nonetheless, just as the interactive robot in experiment 2 was used as a closer approximation to a computer than a human (compared to experiments 1 and 3), the non-interactive robot can be viewed as a closer approximation to a human than a computer. Thus, compared to experiments 1 and 3, experiment 2 provides intermediary stimuli for the explicit social condition for both the human and computer partner conditions, with less of an extreme difference between the two conditions.

A further limitation throughout all experiments was the modest sample size, particularly with the division of participants into separate preference groups, which presents an issue related to statistical power. Thus each of the analyses conducted within this thesis may have lacked sensitivity to detect differences that existed between the social conditions within each preference group. Low power is a particular issue for the explicit social instruction variable because this manipulation had the smallest effect size in each experiment (see chapter 5) and thus required higher statistical power for effects to be detected. Future studies should aim for much larger sample sizes and ideally allocate participants to preference groups on an a priori basis. However, because post-task preferences drove the effects of individual differences in preferences groups within this thesis, such pre-allocation in future studies may not be a viable option. An alternative solution would be to pre-register any future studies, taking into account statistical power issues. In addition, a Bayesian statistical approach is recommended for future research because power is less of an issue within this statistical method.

6.5 FUTURE DIRECTIONS

Despite the promising findings of this thesis, many questions remain unanswered regarding the impact of social factors on rhythmic interpersonal coordination and several new questions have arisen. The distinction between implicit and explicit cues of partner intentionality, and the nature of the differential influence of these cues on co-representation during joint action, require further in-depth investigation. A between-subjects design that extends the current paradigm may be informative here. A situation where some participants experience a more adaptive VP combined with the human partner instruction, as well as a less adaptive VP with the computer partner instruction and vice-versa, in a congruent-incongruent cue format, would offer further insight on this issue. Similarly, a between-subjects design may also help to overcome a limitation of the current design relating to the differentiation between skill and responsiveness. For the purposes of this thesis, higher VP adaptivity was presumed to suggest the partner's increased intention to synchronise; however, it may also be that higher adaptivity may instead indicate a partner who has a greater ability to synchronise. As a within-subjects design was used, participants experienced both apparent partners at all of the different degrees of adaptivity, so the effect of partner's with different abilities can not be inferred but will make for an interesting future application of this research design.

The current paradigm may also be used in the future to answer a different but related question regarding synchronisation and social factors—that of how synchronisation affects social bonding. Much research has demonstrated that interpersonal motor synchrony leads to increased pro-social behaviour (Hoehl et al., 2020; Rennung & Göritz, 2016), increased cooperation and willingness to help a partner (Cirelli et al., 2014; Kokal et al., 2011), increased trust and empathy (Koehne et al., 2016; Launay et al., 2013), and greater liking and affiliation (Cacioppo et al., 2014; Cirelli et al., 2014; Hove & Risen, 2009; Kokal et al., 2011; Marsh et al., 2009; Tarr et al., 2016). Due to the nature of this research, it is challenging to include a clear control condition, making it difficult to determine a causal relationship. In other words, it is hard to know whether it is the synchronisation per se or other factors that contribute to the change in social bonding (e.g. those who like each other more, or are more similar to each other, are better at synchronising together). The adaptive robot design offers a controlled method that may be used to address this issue, where sources of variance can be controlled more vigorously than with a human confederate or paired participant. Here, a design where participants synchronise with two robots with different degrees of adaptivity can be used to ascertain the impact of synchronisation on the degree of liking and affiliation.

A particularly important theme highlighted by the findings of this thesis is the prominent role of individual differences in social-cognitive processes and the dynamic nature of the influence of these individual differences. Further research targeting individual differences in social cognition and personality is imperative to better understand the complexities of human interpersonal movement coordination, and by extension—joint action in general. Of particular importance here is research examining interpersonal coordination within populations with atypical social-cognitive functions, such as those with autism spectrum disorders or social anxiety. Using the VP as a proxy for social interaction, along with the ADAM model to estimate the underlying mechanisms of synchronisation—particularly anticipatory error correction—will allow for a better understanding of self-other integration and segregation within these populations. Indeed, the drumming robot design may be of particular use with these populations and may be a promising method for therapeutic interventions (Lorenz et al., 2016).

Similarly, there is very little research into interpersonal coordination within older adult populations, particularly for those with neurodegenerative conditions such as dementia. General cognitive and sensorimotor function decline with age (Seidler et al., 2010), and with dementia, there is severe cognitive and social-cognitive impairment (Snowden et al., 2003).

However, particularly concerning social-cognitive impairment, the underlying factors and trajectory of decline are poorly understood (Snowden et al., 2003). Among other aspects, research has found that those with dementia show an impaired theory of mind (Fabbri et al., 2018); however, how this relates to co-representation and interpersonal coordination is an open question. In addition, there is a gap in research in relation to individual differences within the ageing population and those with dementia, particularly with regard to social attitudes and preferences.

The current paradigm presents an ideal opportunity for increased understanding of sensorimotor control and interpersonal coordination within older adults and people with dementia, and more importantly, much-needed insight into social-cognitive function. Music therapy is already a commonly practised and effective therapeutic technique used with these populations (Dowson et al., 2019), and social robots are increasingly being considered as therapeutic tools to assist with the care needs of the elderly or those with dementia (Mordoch et al., 2013). The benefits of music therapy on general cognitive ability are well established (Brancatisano et al., 2019; Dowson et al., 2019; MacRitchie et al., 2020); however, the social benefits and effects on social-cognitive factors are often not considered (Dowson et al., 2019; MacRitchie et al., 2020). Thus, the current paradigm will enable not only a better understanding of social-cognitive function but may also potentially provide insight into the mechanisms of music therapy as a therapeutic technique. Moreover, this paradigm will allow for further investigation of human-robot interaction with elderly populations, particularly in relation to how implicit and explicit communicative cues can influence joint performance.

6.6 CONCLUSION

In conclusion, the main finding of this thesis is that extrinsic social factors such as the social context and the intentionality of a synchronisation partner affect rhythmic interpersonal coordination at multiple levels. A key aspect of this influence at behavioural, cognitive, and neural levels relates to the way in which people regulate the integration and segregation of their representations of self and other. However, these effects are mediated by individual differences in intrinsic social factors such as personal preferences and biases. This outcome highlights that top-down processes related to beliefs interact with bottom-up sensorimotor processes during joint action, even when the task is as simple as drumming in time.

Furthermore, the influence of these top-down processes may be different for different people, depending on a multitude of factors such as one's personality, social-cognitive ability, or previous experience interacting with different types of partners. Thus, a major implication of this thesis is the necessity of taking individual differences into account, particularly when investigating social processes during dynamic social interactions, whether this is during human-human interactions or interaction with virtual agents, robots or computers. Moreover, the current findings suggest that beliefs about a partner during social interaction may be just as, or even more so, influential on performance than the actual characteristics of the partner. This carries implications not only for future research into basic psychological mechanisms underpinning rhythmic interpersonal coordination but also for understanding the broader social dynamics of real-life situations that involve cooperative joint action.

In summary, this thesis showed that both extrinsic and intrinsic social factors influence rhythmic interpersonal coordination across multiple levels. Also, in addition to the actual characteristics of the interaction partner, top-down influences on social perception play a prominent role in modulating joint task performance. Finally, this thesis also found that the influence of top-down processes is modulated by individual differences in several social-cognitive factors, highlighting the complexity of understanding human interaction during joint action.

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Appendices

Appendix A. Ethics Approval

Locked Bag 1797
Penrith NSW 2751 Australia
Office of Research Services

ORS Reference: H10344 13/011459

HUMAN RESEARCH ETHICS COMMITTEE

17 October 2013

Associate Professor Peter Keller
The MARCS Institute

Dear Peter,

I wish to formally advise you that the Human Research Ethics Committee has approved your research proposal H10344 “Cognitive, Neural, and Social Mechanisms of Rhythmic Interpersonal Coordination“, until 31 March 2016 with the provision of a progress report annually and a final report on completion.

Conditions of Approval

1. A progress report will be due annually on the anniversary of your approval date.

2. A final report will be due at the expiration of your approval period as detailed in the approval letter.

3. Any amendments to the project must be approved by the Human Research Ethics Committee prior to the project continuing. Amendments must be requested using the HREC Amendment Request Form:
http://www.uws.edu.au/_data/assets/pdf_file/0018/491130/HREC_Amendment_Request_Form.pdf

4. Any serious or unexpected adverse events on participants must be reported to the Human Ethics Committee as a matter of priority.

5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the Committee as a matter of priority

6. Consent forms are to be retained within the archives of the School or Research Institute and made available to the Committee upon request

Please quote the registration number and title as indicated above in the subject line on all future correspondence related to this project. All correspondence should be sent to the email address humanethics@uws.edu.au.

This protocol covers the following researchers:
Peter Keller, Catherine Stevens, Peta Mills

Yours sincerely

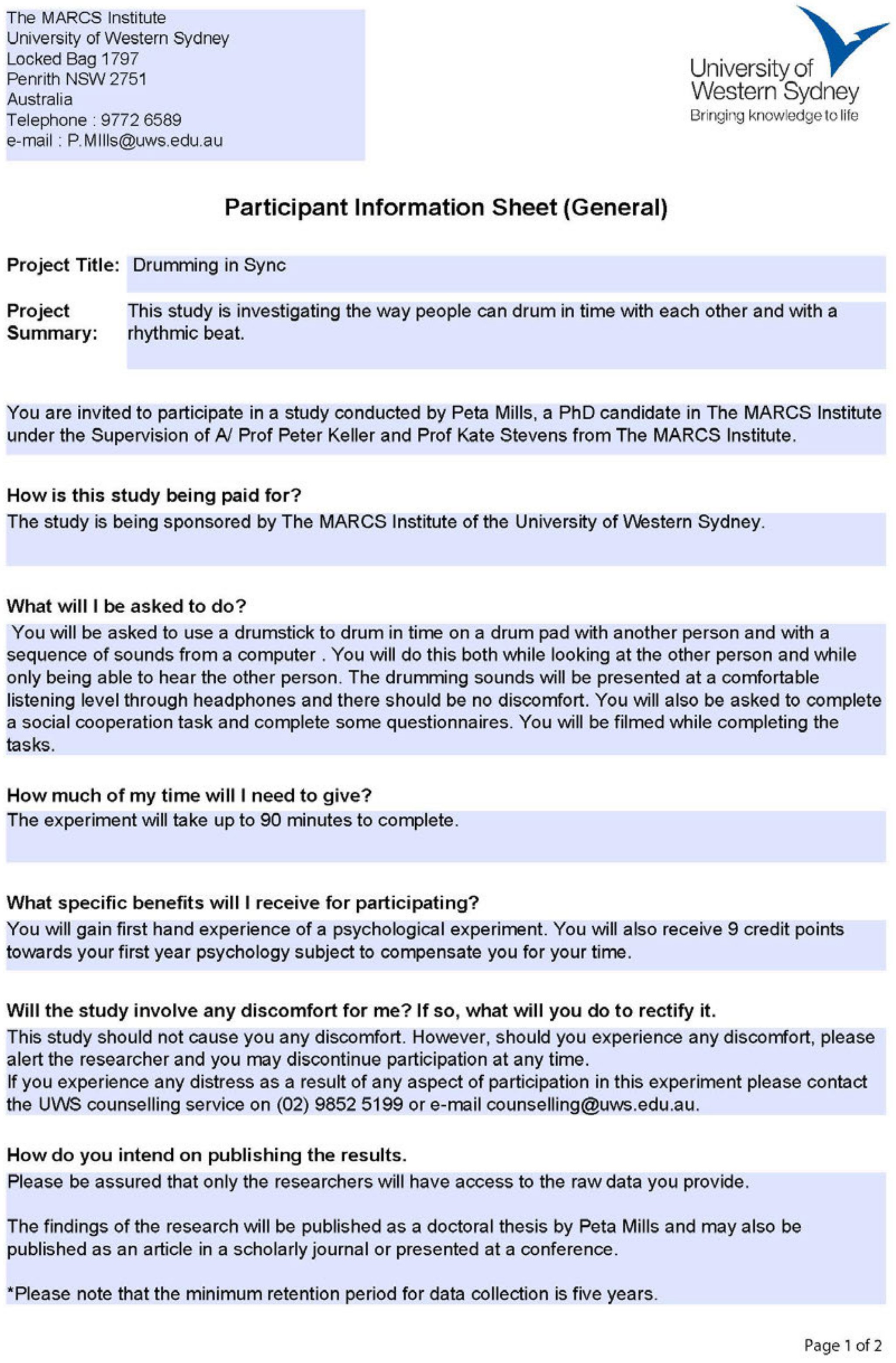
[redacted] [redacted]

A/Professors Debbie Horsfall and Federico Girosi

Deputy Chairs,
Human Researcher Ethics Committee

Appendix B Information Sheets and Consent Forms

Appendix B1: Experiment 1



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University of Western Sydney
Bringing knowledge to life

Participant Information Sheet (General)

Project Title: Drumming in Sync

Project Summary: This study is investigating the way people can drum in time with each other and with a rhythmic beat.

You are invited to participate in a study conducted by Peta Mills, a PhD candidate in The MARCS Institute under the Supervision of A/ Prof Peter Keller and Prof Kate Stevens from The MARCS Institute.

How is this study being paid for?

The study is being sponsored by The MARCS Institute of the University of Western Sydney.

What will I be asked to do?

You will be asked to use a drumstick to drum in time on a drum pad with another person and with a sequence of sounds from a computer . You will do this both while looking at the other person and while only being able to hear the other person. The drumming sounds will be presented at a comfortable listening level through headphones and there should be no discomfort. You will also be asked to complete a social cooperation task and complete some questionnaires. You will be filmed while completing the tasks.

How much of my time will I need to give?

The experiment will take up to 90 minutes to complete.

What specific benefits will I receive for participating?

You will gain first hand experience of a psychological experiment. You will also receive 9 credit points towards your first year psychology subject to compensate you for your time.

Will the study involve any discomfort for me? If so, what will you do to rectify it.

This study should not cause you any discomfort. However, should you experience any discomfort, please alert the researcher and you may discontinue participation at any time.
If you experience any distress as a result of any aspect of participation in this experiment please contact the UWS counselling service on (02) 9852 5199 or e-mail counselling@uws.edu.au.

How do you intend on publishing the results.

Please be assured that only the researchers will have access to the raw data you provide.

The findings of the research will be published as a doctoral thesis by Peta Mills and may also be published as an article in a scholarly journal or presented at a conference.

*Please note that the minimum retention period for data collection is five years.

There are a number of government initiatives in place to centrally store research data and to make it available for further research. For more information, see http://www.ands.org.au/ and http://www.rdsi.uq.edu.au/about. Regardless of whether the information you supply or about you is stored centrally or not, it will be stored securely and it will be de-identified before it is made to available to any other researcher.

Can I withdraw from the study?

Participation is entirely voluntary: and you are not obliged to be involved. If you do participate, you can withdraw at any time without giving any reason.

If you do choose to withdraw, any information that you have supplied will remain confidential.

Can I tell other people about the study?

Yes, you can tell other people about the study by providing them with the chief investigator's contact details. They can contact the chief investigator to discuss their participation in the research project and obtain an information sheet.

What if I require further information?

Please contact Peta Mills or A/ Prof Peter Keller should you wish to discuss the research further before deciding whether or not to participate.

Peta Mills: P.MIlls@uws.edu.au or 9772 6589
A/ Prof Peter Keller: P.Keller@uws.edu.au or 9772 6722

What if I have a complaint?

This study has been approved by the University of Western Sydney Human Research Ethics Committee. The Approval number is H10344.

If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through the Office of Research Services on Tel +61 2 4736 0229 Fax +61 2 4736 0013 or email humanethics@uws.edu.au.

Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

If you agree to participate in this study, you may be asked to sign the Participant Consent Form.

Human Research Ethics Committee
Office of Research Services

University of Western Sydney

Participant Consent Form

This is a project specific consent form. It restricts the use of the data collected to the named project by the named investigators.

Note: If not all of the text in the row is visible please 'click your cursor' anywhere on the page to expand the row. To view guidance on what is required in each section 'hover your cursor' over the bold text.

Project Title: Drumming in Sync

I,…………………………, consent to participate in the research project titled 'Drumming in Sync'.

I acknowledge that:

I have read the participant information sheet and have been given the opportunity to discuss the information and my involvement in the project with the researcher/s.

The procedures required for the project and the time involved have been explained to me, and any questions I have about the project have been answered to my satisfaction.

I consent to the drumming task, the cooperation task, and to the questionnaires.

I consent to be filmed during the task and understand that the footage will remain confidential and only the researchers may access it.

I understand that my involvement is confidential and that the information gained during the study may be published but no information about me will be used in any way that reveals my identity.

I understand that I can withdraw from the study at any time, without affecting my relationship with the researcher/s now or in the future.

Signed:

Name:

Date:

Return Address: Peta Mills, University of Western Sydney, The MARCS Institute, Bankstown Campus, Locked Bag 1797, Penrith, NSW, 2751 P.Mills@uws.edu.au 02 9772 6589

This study has been approved by the University of Western Sydney Human Research Ethics Committee.

The Approval number is: H10344

If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through the Office of Research Services on Tel +61 2 4736 0229 Fax +61 2 4736 0013 or email humanethics@uws.edu.au. Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

Appendix B2: Experiment 2

WESTERN SYDNEY
UNIVERSITY

Participant Information Sheet

Project Title: ***"The Rhythmic Robot: Drumming in time with a robot"***

Project Summary:

You are invited to participate in a study conducted by PhD candidate Peta Mills of The MARCS Institute under the supervision of Peter Keller. This research tests a newly developed drumming robot program. This program is designed to have the robot drum a steady beat or rhythm, keeping in time with the participant.

How is the study being paid for?

The study is being sponsored by The MARCS Institute of Western Sydney University

What will I be asked to do?

Participation will involve drumming on a drum pad in time with a robot.

You will also complete some questionnaires and respond to some short demographic questions. You do not need to have any musical experience to participate. The sounds will be presented at comfortable listening levels and there should be no discomfort.

How much of my time will I need to give?

The task should take approximately 90 minutes to complete.

What benefits will I, and/or the broader community, receive for participating?

You will gain first- hand experience of a psychological experiment. You will also receive 9 credit points towards your first year psychology subject to compensate you for your time.

Will the study involve any risk or discomfort for me? If so, what will be done to rectify it?

This study should not cause you any discomfort. However, should you experience any discomfort, please alert the researcher and you may discontinue participation at any time.

How do you intend to publish or disseminate the results?

It is anticipated that the results of this research project will be published and/or presented in a variety of forums. In any publication and/or presentation, information will be provided in such a way that the participant cannot be identified, except with your permission. All data will be de-identified and stored in a password protected secure location.

Will the data and information that I have provided be disposed of?

No. Your data will be used as per Western Sydney University's Open Access Policy. This means that data collected from this study can be made available online and world-wide in perpetuity.

Can I withdraw from the study?

Participation is entirely voluntary and you are not obliged to be involved. If you do participate you can withdraw at any time without giving reason by informing the experimenter.

.

If you do choose to withdraw, any information that you have supplied will remain confidential and will not be used as part of the analysis.

Can I tell other people about the study?

Yes, you can tell other people about the study by providing them with the Chief Investigator's contact details. They can contact the Chief Investigator to discuss their participation in the research project and obtain a copy of the information sheet.

What if I require further information?

Please contact Peta Mills or Professor Peter Keller should you wish to discuss the research further before deciding whether or not to participate.

Peta Mills: P.MIlls@westernsydney.edu.au or 9772 6589

A/ Prof Peter Keller: P.Keller@westernsydney.edu.au or 9772 6722

What if I have a complaint?

If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through Research Engagement, Development and Innovation (REDI) on Tel +61 2 4736 0229 or email humanethics@westernsydney.edu.au

Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

If you agree to participate in this study, you may be asked to sign the Participant Consent Form. The information sheet is for you to keep and the consent form is retained by the researcher/s.

This study has been approved by the Western Sydney University Human Research Ethics Committee. The Approval number is H10344

WESTERN SYDNEY
UNIVERSITY

Consent Form

Project Title: ***"The Rhythmic Robot: Drumming in time with a robot"***

I hereby consent to participate in the above named research project.

I acknowledge that:

- I have read the participant information sheet (or where appropriate, have had it read to me) and have been given the opportunity to discuss the information and my involvement in the project with the researcher/s
- The procedures required for the project and the time involved have been explained to me, and any questions I have about the project have been answered to my satisfaction.

I consent to:

☐ Participate in the drumming tasks.

☐ The recording of my drumming performance during the experiment.

☐ Answering post-experiment questions used to assess personality and music experience.

Data publication, reuse and storage

This project seeks consent for the data provided to be used in any other projects in the future.

To make reuse of the data possible it will be stored under Western Sydney University's Open Access Policy.

I understand that:

☐ In relation to publication of the data my involvement is confidential and the information gained during the study may be published but no information about me will be used in any way that reveals my identity.

☐ The researchers intend to make the non-identified data from this project available for other research projects.

☐ I can withdraw from the study at any time without affecting my relationship with the researcher/s, and any organisations involved, now or in the future.

Signed:

Name:

Date:

This study has been approved by the Human Research Ethics Committee at Western Sydney University. The ethics reference number is: H*10344*

What if I have a complaint?

If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through Research Engagement, Development and Innovation (REDI) on Tel +61 2 4736 0229 or email humanethics@westernsydney.edu.au.

Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

Appendix B3. Experiment 3

The MARCS Institute
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e-mail : P.MIlls@uws.edu.au

University of Western Sydney
Bringing knowledge to life

Participant Information Sheet (General)

Project Title: **The Rhythmic Brain: Drumming in synchrony and EEG**

Project Summary: This study is investigating brain activity when people are drumming in time with each other and a rhythmic beat.

You are invited to participate in a study conducted by Peta Mills, a PhD candidate in The MARCS Institute under the Supervision of A/ Prof Peter Keller and Prof Kate Stevens from The MARCS Institute.

How is this study being paid for?

The study is being sponsored by The MARCS Institute of the University of Western Sydney.

What will I be asked to do?

Participation will involve drumming on a drum pad in time with a sequence of sounds from a computer presented over special headphones that fit inside your ear.

While you are doing these tasks, we will record your brain activity using EEG (Electroencephalogram). A cap containing multiple sensors will be placed on your head, allowing the EEG system to detect your brain's electrical activity at the scalp surface as you synchronise your movements with the different stimuli. In order to obtain a good measure of your brain activity, a conductive gel will placed on your scalp where the sensors are attached. This gel can be washed away after the experiment. EEG does not interfere with brain activity and presents no known health risk.

You will also complete some questionnaires and respond to some short demographic questions.

How much of my time will I need to give?

The experiment will take up to 120 minutes to complete.

What specific benefits will I receive for participating?

You will gain first hand experience of a psychological experiment. You will also receive 12 credit points towards your first year psychology subject to compensate you for your time.

Will the study involve any discomfort for me? If so, what will you do to rectify it.

This study should not cause you any discomfort. However, should you experience any discomfort, please alert the researcher and you may discontinue participation at any time.

How do you intend on publishing the results.

Please be assured that only the researchers will have access to the raw data you provide.

The findings of the research will be published as a doctoral thesis by Peta Mills and may also be published as an article in a scholarly journal or presented at a conference.

*Please note that the minimum retention period for data collection is five years.

There are a number of government initiatives in place to centrally store research data and to make it available for further research. For more information, see http://www.ands.org.au/ and http://www.rdsi.uq.edu.au/about. Regardless of whether the information you supply or about you is stored centrally or not, it will be stored securely and it will be de-identified before it is made to available to any other researcher.

Can I withdraw from the study?

Participation is entirely voluntary: and you are not obliged to be involved. If you do participate, you can withdraw at any time without giving any reason.

If you do choose to withdraw, any information that you have supplied will remain confidential.

Can I tell other people about the study?

Yes, you can tell other people about the study by providing them with the chief investigator's contact details. They can contact the chief investigator to discuss their participation in the research project and obtain an information sheet.

What if I require further information?

Please contact Peta Mills or A/ Prof Peter Keller should you wish to discuss the research further before deciding whether or not to participate.

Peta Mills: P.MIlls@uws.edu.au or 9772 6589
A/ Prof Peter Keller: P.Keller@uws.edu.au or 9772 6722

What if I have a complaint?

This study has been approved by the University of Western Sydney Human Research Ethics Committee. The Approval number is [H10487]

If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through the Office of Research Services on Tel +61 2 4736 0229 Fax +61 2 4736 0013 or email humanethics@uws.edu.au.

Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

If you agree to participate in this study, you may be asked to sign the Participant Consent Form.

Human Research Ethics Committee
Office of Research Services

University of Western Sydney

Participant Consent Form

This is a project specific consent form. It restricts the use of the data collected to the named project by the named investigators.

Note: If not all of the text in the row is visible please 'click your cursor' anywhere on the page to expand the row. To view guidance on what is required in each section 'hover your cursor' over the bold text.

Project Title: The Rhythmic Brain: Drumming in Synchrony and EEG

I,............................., consent to participate in the research project titled 'The Rhythmic Brain: Drumming in Synchrony and EEG'.

I acknowledge that:

I have read the participant information sheet and have been given the opportunity to discuss the information and my involvement in the project with the researcher/s.

The procedures required for the project and the time involved have been explained to me, and any questions I have about the project have been answered to my satisfaction.

I consent to the electrodes being attached to me, the conducting gel being placed on my scalp, the drumming task and to the questionnaires.

I understand that my involvement is confidential and that the information gained during the study may be published but no information about me will be used in any way that reveals my identity.

I understand that I can withdraw from the study at any time, without affecting my relationship with the researcher/s now or in the future.

Signed:

Name:

Date:

Return Address: Peta Mills, University of Western Sydney, The MARCS Institute, Bankstown Campus, Locked Bag 1797, Penrith, NSW, 2751 P.Mills@uws.edu.au 02 9772 6589

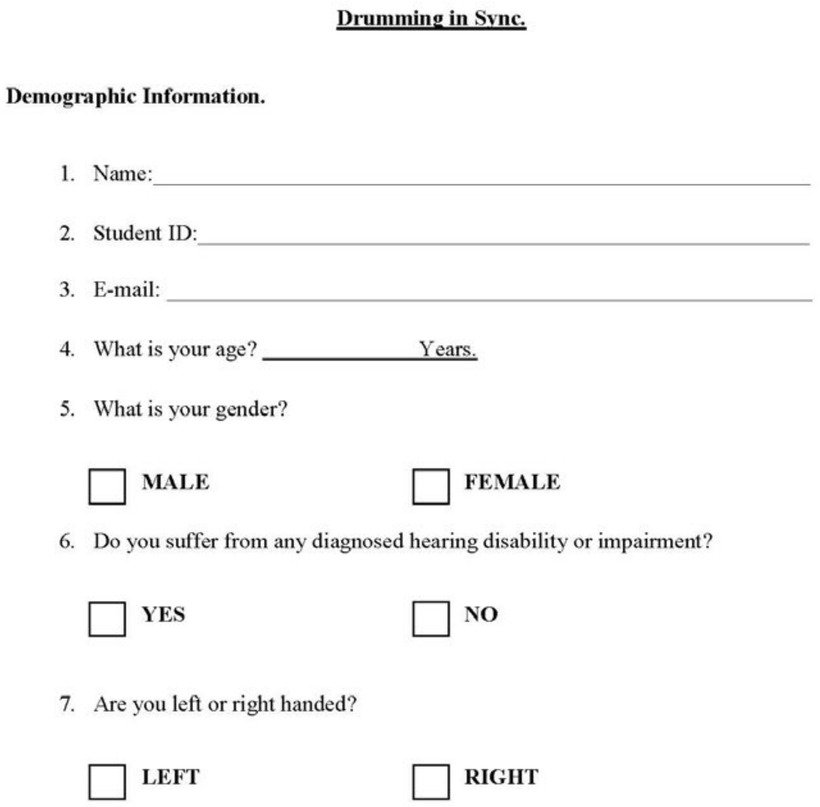
This study has been approved by the University of Western Sydney Human Research Ethics Committee.

The Approval number is: H10487

If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through the Office of Research Services on Tel +61 2 4736 0229 Fax +61 2 4736 0013 or email humanethics@uws.edu.au. Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

Appendix C Questionnaires

Appendix C1. Demographic Questionnaire Experiments 1 and 2



Drumming in Sync.

Demographic Information.

1. Name:____
2. Student ID:____
3. E-mail: ____
4. What is your age? _____________Years.
5. What is your gender?

   ☐ **MALE** ☐ **FEMALE**

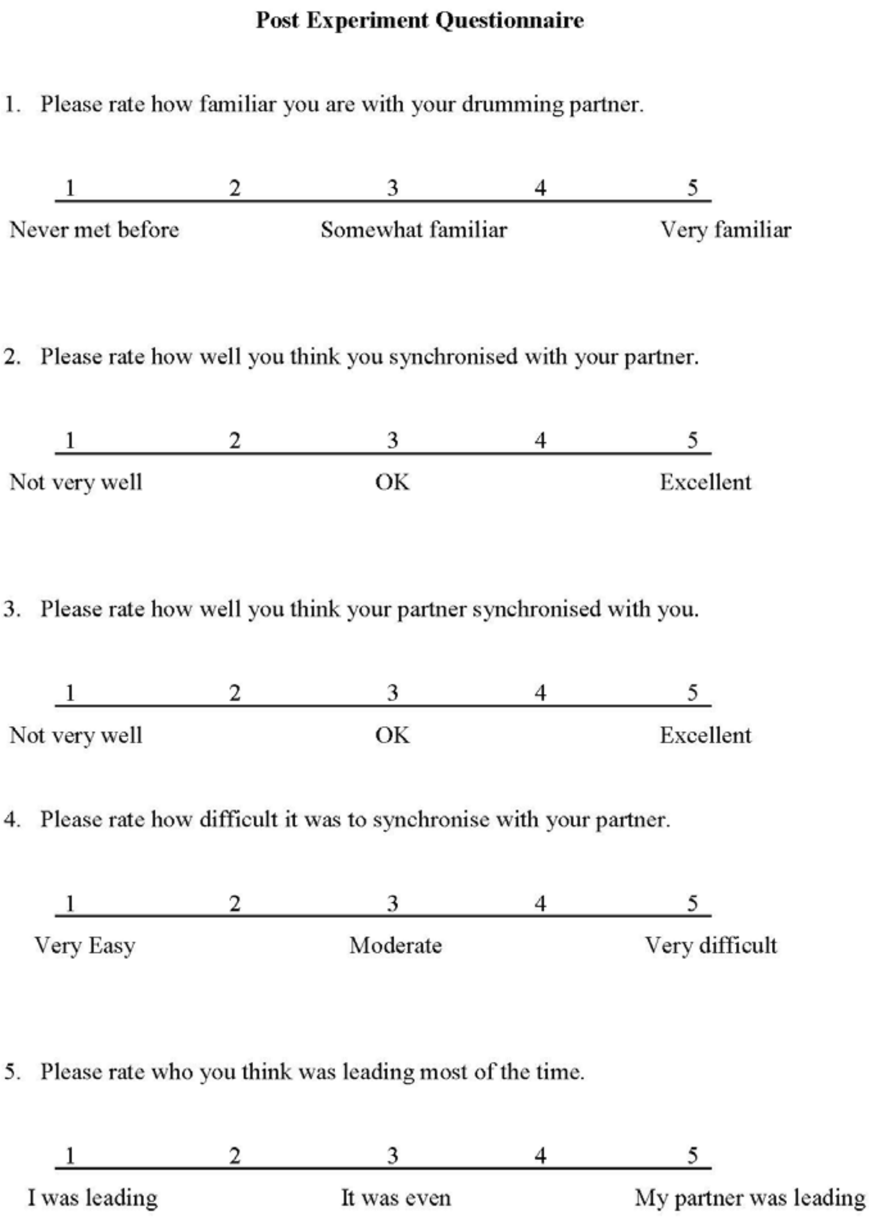
6. Do you suffer from any diagnosed hearing disability or impairment?

   ☐ **YES** ☐ **NO**

7. Are you left or right handed?

   ☐ **LEFT** ☐ **RIGHT**

Appendix C2. Post Experiment Questionnaire Experiment 1



Post Experiment Questionnaire

1. Please rate how familiar you are with your drumming partner.

1	2	3	4	5
Never met before		Somewhat familiar		Very familiar

2. Please rate how well you think you synchronised with your partner.

1	2	3	4	5
Not very well		OK		Excellent

3. Please rate how well you think your partner synchronised with you.

1	2	3	4	5
Not very well		OK		Excellent

4. Please rate how difficult it was to synchronise with your partner.

1	2	3	4	5
Very Easy		Moderate		Very difficult

5. Please rate who you think was leading most of the time.

1	2	3	4	5
I was leading		It was even		My partner was leading

6. Please rate how difficult it was to synchronise with the computer tones.

1	2	3	4	5
Very Easy		Moderate		Very difficult

7. In which condition was it easiest to synchronise?
   - ☐ When I was instructed to synchronise with my partner
   - ☐ When I was instructed to synchronise with the computer
   - ☐ It was the same

8. Please describe how much effort you believe your partner put in.

9. Was there anything unusual about the procedure?

Music Training

10. Have you ever studied any kind of music on a regular and individual or group basis?

☐ **YES** ☐ **NO (Go to question 14)**

11. If yes, for each age period, please specify:

AGE PERIOD (E.g. Ages 10-12)	INSTRUMENT and/or SPECIFICATION	AVERAGE NO. HRS/WK

12. Have you ever studied music theory? If so, how extensively? (I.e. levels achieved or courses taken)

---

13. How many years of private music lessons have you received?

If you have received lessons on more than one instrument, including voice, give the number of years for the one instrument/voice you've studied longest. If you have never received private lessons, answer with zero.

_____ years of private lessons

14. Which category comes nearest to the amount of time you currently spend practicing an instrument (or voice)? Count individual practice time only; not group rehearsals.

- ○ I rarely or never practice singing or playing an instrument
- ○ About 1 hour per month
- ○ About 1 hour per week
- ○ About 15 minutes per day
- ○ About 1 hour per day
- ○ More than 2 hours per day

15. Which option best describes your experience at composing music?

- ○ Have never composed any music
- ○ Have composed bits and pieces, but have never completed a piece of music
- ○ Have composed one or more complete pieces, but none have been performed
- ○ Have composed pieces as assignments or projects for one or more music classes; one or more of my pieces have been performed and/or recorded within the context of my educational environment
- ○ Have composed pieces that have been performed for a local audience
- ○ Have composed pieces that have been performed for a regional or national audience (e.g., nationally known performer or ensemble, major concert venue, broadly distributed recording)

16. To the best of your memory, how many live concerts (of any style, with free or paid admission) have you attended as an audience member in the <u>past 12 months?</u> Please do not include regular religious services in your count, but you may include special musical productions or events.
    - ○ None
    - ○ 1 – 4
    - ○ 5 -8
    - ○ 9 – 12
    - ○ 13 or more

17. Which title best describes you?
    - ○ Nonmusician
    - ○ Music-loving nonmusician
    - ○ Amateur musician
    - ○ Serious amateur musician
    - ○ Semiprofessional musician
    - ○ Professional musician

Dance Training

18. Have you undertaken any **dance** training?

☐ **YES** ☐ **NO**

If yes, for each age period, please specify:

AGE PERIOD (E.g. Ages 10-12)	DANCE TYPE and/or SPECIFICATION	AVERAGE NO. HRS/WK

14. **Thank you for participating!**

Appendix C3. Godspeed Questionnaire Experiment 2

GODSPEED I: ANTHROPOMORPHISM

Please rate your impression of the robot on these scales:
以下のスケールに基づいてこのロボットの印象を評価してください。

Fake 偽物のような	1	2	3	4	5	Natural 自然な
Machinelike 機械的	1	2	3	4	5	Humanlike 人間的
Unconscious 意識を持たない	1	2	3	4	5	Conscious 意識を持っている
Artificial 人工的	1	2	3	4	5	Lifelike 生物的
Moving rigidly ぎこちない動き	1	2	3	4	5	Moving elegantly洗練された動き

GODSPEED II: ANIMACY

Please rate your impression of the robot on these scales:
以下のスケールに基づいてこのロボットの印象を評価してください。

Dead 死んでいる	1	2	3	4	5	Alive 生きている
Stagnant 活気のない	1	2	3	4	5	Lively 生き生きとした
Mechanical 機械的な	1	2	3	4	5	Organic 有機的な
Artificial 人工的な	1	2	3	4	5	Lifelike 生物的な
Inert 不活発な	1	2	3	4	5	Interactive 対話的な
Apathetic 無関心な	1	2	3	4	5	Responsive 反応のある

GODSPEED III: LIKEABILITY

Please rate your impression of the robot on these scales:
以下のスケールに基づいてこのロボットの印象を評価してください。

Dislike 嫌い	1	2	3	4	5	Like 好き
Unfriendly 親しみにくい	1	2	3	4	5	Friendly 親しみやすい
Unkind 不親切な	1	2	3	4	5	Kind 親切な
Unpleasant 不愉快な	1	2	3	4	5	Pleasant 愉快な
Awful ひどい	1	2	3	4	5	Nice 良い

GODSPEED IV: PERCEIVED INTELLIGENCE

Please rate your impression of the robot on these scales:
以下のスケールに基づいてこのロボットの印象を評価してください。

Incompetent 無能な	1	2	3	4	5	Competent 有能な
Ignorant 無知な	1	2	3	4	5	Knowledgeable 物知りな
Irresponsible 無責任な	1	2	3	4	5	Responsible 責任のある
Unintelligent 知的でない,	1	2	3	4	5	Intelligent 知的な
Foolish 愚かな	1	2	3	4	5	Sensible 賢明な

GODSPEED V: PERCEIVED SAFETY

Please rate your emotional state on these scales:
以下のスケールに基づいてあなたの心の状態を評価してください。

Anxious 不安な	1	2	3	4	5	Relaxed 落ち着いた
Agitated 動揺している	1	2	3	4	5	Calm 冷静な
Quiescent 平穏な	1	2	3	4	5	Surprised 驚いた

Appendix C4. Post-Experiment Questionnaire Experiment 2

Post Experiment Questionnaire

1. Please rate how well you think you synchronised with the robot.

1	2	3	4	5
Not very well		OK		Excellent

2. Which version of the program do you think synchronised with you better?

   ☐ SocialBot
   ☐ MetroBot
   ☐ It was the same

   Why? ____

3. Please rate how well you think SocialBot synchronised with you.

1	2	3	4	5
Not very well		OK		Excellent

4. Please rate how well you think MetroBot synchronised with you.

1	2	3	4	5
Not very well		OK		Excellent

5. Which version of the program was easier to synchronise with?

    ☐ SocialBot
    ☐ MetroBot
    ☐ It was the same

    Why?

    ____
    ____
    ____
    ____
    ____

6. Please rate how difficult it was to synchronise with SocialBot.

1	2	3	4	5
Very Easy		Moderate		Very difficult

7. Please rate how difficult it was to synchronise with MetroBot.

1	2	3	4	5
Very Easy		Moderate		Very difficult

8. Please rate who you think was leading most of the time during the SocialBot trials.

1	2	3	4	5
I was leading		It was even		SocialBot was leading

9. Please rate who you think was leading most of the time during the MetroBot trials.

1	2	3	4	5

I was leading	It was even	MetroBot was leading

10. Was there anything unusual about the procedure?

____

____

____

____

11. Do you think it is easier for a musician to rehearse with another person or a robot?

☐ Another person
☐ A robot
☐ It is the same

12. **Thank you for participating!**

Appendix C5 Pre-Experiment Questionnaire Experiment 3

Drumming in Sync.

1. Name:____
2. Student ID:____
3. E-mail: ____
4. What is your age? ____________ Years.
5. What is your gender?

☐ **MALE** ☐ **FEMALE**

6. Do you suffer from any diagnosed hearing disability or impairment?

☐ **YES** ☐ **NO**

7. Are you left or right handed?

☐ **LEFT** ☐ **RIGHT**

8. Do you think it will be easier to synchronise with your partner or the computer?
   - ☐ It will be easier to synchronise with my partner
   - ☐ It will be easier to synchronise with the computer
   - ☐ It will be the same
9. Do you think you will be better synchronising with your partner or with the computer?
   - ☐ I will be better when synchronising with my partner
   - ☐ I will be better when synchronising with the computer
   - ☐ I will perform the same

Appendix C6 –Attitudes towards Computers Questionnaire Experiment 3

This Question contains eight pairs of adjectives that are used to describe computers. Please indicate the number that best reflects your opinion. Think of computers in general terms and do not dwell on each specific answer.

	1	2	3	4	5	6	7	
	1	2	3	4	5	6	7	
Restrain creativity	○	○	○	○	○	○	○	Enhance creativity
Helpful	○	○	○	○	○	○	○	Harmful
Enjoyable to use	○	○	○	○	○	○	○	Frustrating to use
Boring	○	○	○	○	○	○	○	Intriguing
A sound investment	○	○	○	○	○	○	○	A waste of money
Difficult to use	○	○	○	○	○	○	○	Easy to use
Non-threatening	○	○	○	○	○	○	○	Threatening
Decrease productivity	○	○	○	○	○	○	○	Increase productivity

Q2 It is easier to work with...

	1	2	3	4	5	6	7	
	1	2	3	4	5	6	7	
Another Person	○	○	○	○	○	○	○	A Computer

Q3 I would prefer to work with....

	1	2	3	4	5	6	7	
	1	2	3	4	5	6	7	
Another Person	○	○	○	○	○	○	○	A Computer

End of Block: Attitudes towards computers instrument

Appendix C7 Post Experiment Questionnaire Experiment 3

1. Please rate how familiar you are with your drumming partner.

1 2 3 4 5

Never met before Somewhat familiar Very familiar

2. Please rate how well you think you synchronised with your partner.

1 2 3 4 5

Not very well OK Excellent

3. Please rate how well you think your partner synchronised with you.

1 2 3 4 5

Not very well OK Excellent

4. Please rate how difficult it was to synchronise with your partner.

1 2 3 4 5

Very Easy Moderate Very difficult

5. Please rate who you think was leading most of the time.

1 2 3 4 5

I was leading It was even My partner was leading

6. Please rate how difficult it was to synchronise with the computer tones.

1 2 3 4 5

Very Easy Moderate Very difficult

7. In which condition was it easiest to synchronise?

   ☐ When I was instructed to synchronise with my partner
   ☐ When I was instructed to synchronise with the computer
   ☐ It was the same

8. Please describe how much effort you believe your partner put in.

9. Was there anything unusual about the procedure?

10. Do you think it is easier for a musician to rehearse with another person or a computer?

    ☐ Another person
    ☐ A computer
    ☐ It is the same

11. **Thank you for participating!**