Behavioural and Electrophysiological Indices of Error Processing and Perception in Joint Musical Action

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Statement of Authentication

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

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Abstract

Errors are rare, important events. During joint action, agency of errors helps initiate corrective, adaptive responses. If agency becomes ambiguous, errors may become more difficult to process. Models of joint action posit that internal models are developed for own and others' actions during joint action. If agency is ambiguous, own and other internal models may overlap, causing confusion as to who produced what action. Further, claiming agency over past actions, whether performed, observed, or neither, may affect neural indices of past performance and past errors. The first experiment investigated how agency ambiguity affects behavioural and neural responses to errors and the role of agency in models of joint action. Results from this experiment showed no effects of the agency manipulation, but revealed differences in how distinct types of errors are processed. Uncorrected errors showed a pattern of performance breakdown and were processed at initiation of the erroneous motor command. Corrected errors showed a pattern of pre-response conflict and were processed after the error onset. The second experiment investigated the role of belief of agency on behavioural and neural indices of the perception of errors in previously performed actions. Results showed participants struggled to identify the performer and errors in past performance, but neural activity suggested familiarity may have aided in processing of previously performed actions. Overall findings suggest the brain supports fluent interpersonal coordination in real-time joint action by employing distinct neural mechanisms to manage different types of errors and that a sense of familiarity may play a role in the processing of previously performed actions.

Chapter 1

Literature Review

Errors are rare and important events, ranging from small errors like misjudging a step to larger errors like mistiming the travel time to a job interview. Errors generally have consequences, be it as simple as losing balance after that misplaced step or more serious, as having to explain lateness to a potential future employer. Although errors come with consequences, they are a useful and necessary part of learning and skill acquisition. Errors initiate behavioural adaptation when the errors are recognised as such (Ullsperger & von Cramon, 2004). Errors become more complex when more people are involved, such as in cooperative activities like carrying a piece of furniture together or playing a team sport. Errors committed by any actor have consequences that usually affect the other actors, although not necessarily to the same degree. For example, a teammate may miss an opportunity to score a goal – this error is felt equally by the whole team. However, if a man is helping a friend move a couch and the man loses grip, dropping the couch on his toe, he will suffer a more damaging consequence than the couch owner. Alternatively, if the man drops the couch and it ends up breaking, the friend will have a more damaging consequence, even though she is not the one who committed the error. In both of these scenarios, progress to the shared goal of moving the couch is affected. Thus, in cooperative activities, errors of one person can have varying consequences on those involved and progress toward the shared goal is affected.

Responses and adaptation to errors become increasingly complex when there is confusion as to who performed the action. When people are performing the same action at the same time with the same intended outcome, people can be confused as to who was responsible for the action (Farrer & Frith, 2002). The agent of the action becomes less clear and both performers may think their own actions resulted in the outcome. It is important for performance monitoring to quickly identify ownership of errors in order to ensure subsequent accuracy and enact adaptation of behaviour, if necessary.

This chapter will outline the behavioural and neural indices of error processing and how joint action and agency ambiguity affect these responses. I will discuss why music performance was chosen specifically to investigate these effects. Perception and identification of errors within joint action will be discussed. The final section sets out the overall aims and proposed contribution of the current studies. The second and third chapters provide detailed reports of the experiments conducted for this dissertation. Both of these chapters are written as free-standing manuscripts. The final chapter provides a summary of the findings, limitations, and how the findings and conclusions fit into the literature.

1.1 Error Processing

1.1.1 Behavioural Responses of Error Processing

Previous research in error processing and performance monitoring has provided an understanding of behavioural responses to errors. Behaviourally, errors are often preceded by speeded responses and followed by slower responses (for a review, see Danielmeier & Ullsperger, 2011), reflecting a speed-accuracy trade-off (Wickelgren, 1977). These responses have been reliably reproduced in discrete tasks, such as a series of trials in a speeded reaction-time task. Theories explaining post-error slowing include the cognitive control theory, the orienting theory, the inhibition theory, and the adaptive orienting theory.

The cognitive control theory suggests that post-error slowing is an indication of increased cognitive control after an error is made (Gehring & Fencsik, 2001). This theory posits that post-error behavioural adjustments are engaged through top-down processes controlled by a performance monitoring system, which has been associated with the posterior medial frontal cortex in the brain (Danielmeier & Ullsperger, 2011). The increased cognitive control is thought to improve accuracy on subsequent responses, giving post-error slowing a practical and functional purpose. In this sense, post-error slowing may allow for more time to prepare the subsequent response (Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). However, some studies demonstrate that post-error slowing does not improve accuracy in subsequent trials (Danielmeier & Ullsperger, 2011; Hajcak, McDonald, & Simons, 2003).

The orienting theory suggests that post-error slowing is an orienting response to an unexpected event, as errors are usually rare, accidental events (Notebaert et al., 2009; Núňez Castellar, Kühn, Fias, & Notebaert, 2010). In this theory, post-error slowing reflects a shift of attention, orienting attention to the unexpected event. This orienting of attention then delays the subsequent response. Research shows a pattern of slowing following infrequent correct responses similar to that of infrequent error responses (Notebaert et al., 2009; Núňez Castellar et al., 2010). Post-error slowing is observed when errors are rare events, but not when they are common events (Ullsperger & Szymanowski, 2004). Additionally, a study using oddball (i.e., infrequent) events has reported slowed responses after infrequent, non-error events (Barcelo, Escera, Corral, & Periáñez, 2006). This suggests that post-response slowing is not exclusive to error responses, but may be observed after any infrequent response type. However, post-error slowing is not observed in studies that involved infrequent manipulated feedback (de Bruijn, Mars, & Hulstijn, 2004; Logan & Crump, 2010; Steinhauser & Kiesel, 2011). As these manipulations were also rare, this suggests that post-error slowing cannot be explained merely by frequency of response.

The inhibition theory suggests that post-error slowing is related to response inhibition. Activation of an incorrect response leads to the suppression of the subsequent response (Ridderinkhof, 2002). This idea is supported by functional magnetic resonance imaging (fMRI) research, showing a decrease in motor activity during trials that have increased post-error slowing (Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011; King, Korb, von Cramon, & Ullsperger, 2010). Cortical areas shown to be involved in post-error slowing include the pre-supplementary motor area, the lateral inferior frontal cortex, and the subthalamic nucleus. These areas are also involved in motor inhibition (Aron, Robbins, & Poldrack, 2004, 2014; Siegert et al., 2014). In electroencephalography (EEG), post-error slowing has been correlated with an increase in beta band power (Marco-Pallarés, Camara, Münte, & Rodríguez-Fornells, 2008), and this increase has been associated with motor inhibition (Marco-Pallarés et al., 2008; Pogosyan, Gaynor, Eusebio, & Brown, 2009; Swann et al., 2009). When performance is expected to be fast and continuous, these inhibitory processes may not affect performance. Some research suggests that inhibition is an expression of increased cognitive control, thereby combining these two theories (Marco-Pallarés et al., 2008), and even further, that inhibition is related to infrequent responses more generally (Aron et al., 2014; Wessel & Aron, 2013), consistent with the orienting theory. The adaptive orienting theory combines aspects of the inhibition and orienting theories into a broader theory that explains responses to errors along with response to unexpected events more generally.

The adaptive orienting theory suggests that errors fall under the umbrella of surprise or unexpected events (Wessel & Aron, 2017). This theory accounts for the observations and conclusions associated with the previous theories, although from a different perspective. Unexpected events violate our predictions, resulting in a cascade of cognitive and behavioural reactions different from those elicited when predictions are met. This theory is not specific to error-processing, but covers it within its scope. Here, unexpected events include action errors, unexpected action outcomes, and unexpected perceptual events (Wessel & Aron, 2017).

Errors fall into the category of action errors. Unexpected events mobilise a fronto-basal-ganglia network for stopping, impacting cognition and behaviour (Wessel & Aron, 2017). This suggests ongoing prediction and feedback or comparison with the prediction, as do previous theories. When an action is performed with a predicted outcome and an error is made, it results in a mismatch between the prediction and action outcome. The mismatch triggers a global motor suppression which can be observed behaviourally as post-error slowing. This allows for the actor to alter their action plan in order to fix the error, or at least react to it in some way (Wessel, 2018). In most experiments, there is little opportunity to fix errors but post-error slowing is still observed. However, in tasks where slowing or stopping could impact future performance, slowing can be reduced. For example, in music ensemble performance, stopping or even slowing mid-performance due to a misplayed note would affect the remainder of the performance. Novice musicians have a tendency to ignore errors and keep playing or stop all together, while expert musicians have more strategies to deal with errors (i.e., exploration within the musical parameters and techniques) that will allow them to continue playing without disrupting the performance (Kruse-Weber & Parncutt, 2014). However, when playing on their own, musicians do slow their performance post-error (Maidhof, Rieger, Prinz, & Koelsch, 2009; Ruiz, Jabusch, & Altenmüller, 2009).

These theories provide explanations for the behavioural response to errors. Support for these theories may depend on the types of trials or priority of the task (e.g., speed or accuracy). Because the adaptive orienting theory incorporates elements of the other theories and extends beyond just error processing to a broader theory of unexpected events, this theory is used as a framework for the research done here. Neural activity during action errors provides another layer to the overall understanding of error processing and may provide support for the various theories of post-error slowing.

1.1.2 Neural Indices of Error Processing

The neural activity associated with errors has been predominantly investigated using EEG. EEG research has revealed a consistent pattern of event-related potentials (ERPs) in response to errors (see Figure 1.1). The error-related negativity (ERN) is a negative component that peaks around 50 to 100 milliseconds (ms) following error onset and presents a fronto-central scalp distribution (for a review, see Gehring, Liu, Orr, & Carp, 2012).

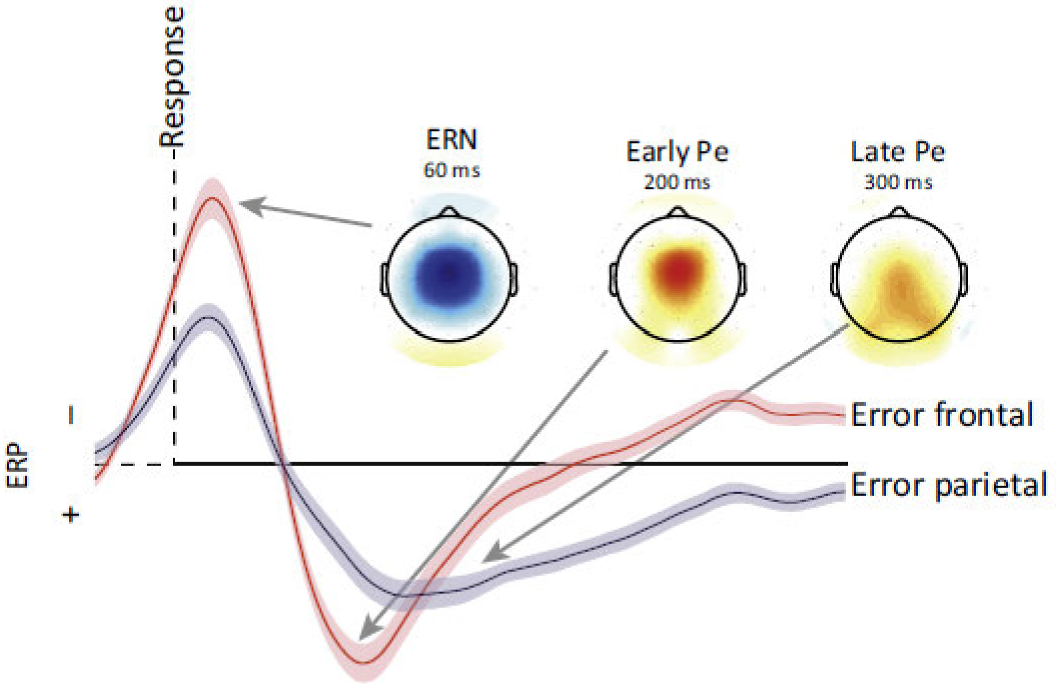


Figure 1.1. Latencies and topographies of the error-related negativity (ERN) and error positivity (Pe). From Ullsperger, Fischer, et al. (2014).

The ERN is thought to be generated in the posterior medial frontal cortex, more specifically in the anterior midcingulate cortex (see Figure 1.2; Gehring et al., 2012; Ullsperger, Danielmeier, & Jocham, 2014). The ERN is a multi-modal component that can be elicited by errors involving stimuli presented to the visual, auditory, and somatosensory systems (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Forster, Forster, & Pavone, 2008; Gehring, Goss, Coles, Meyer, & Donchin, 1993) and by errors committed by unimanual, bimanual, foot, oculomotor, and vocal responses (Endrass, Franke, & Kathmann, 2005; Falkenstein et al., 1991; Gehring et al., 1993; Holroyd, Dien, & Coles, 1998; Masaki, Tanaka, Takasawa, & Yamazaki, 2001; Murata & Katayama, 2005). The ERN can be elicited through a variety of tasks, including flanker tasks, stroop tasks, go/nogo tasks, and sequential tasks such as piano playing and typing (Kalfaoğlu, Stafford, & Milne, 2018; Maidhof, Pitkaniemi, & Tervaniemi, 2013; Maidhof et al., 2009; Riesel, Weinberg, Endrass, Meyer, & Hajcak, 2013; Ruiz et al., 2009).

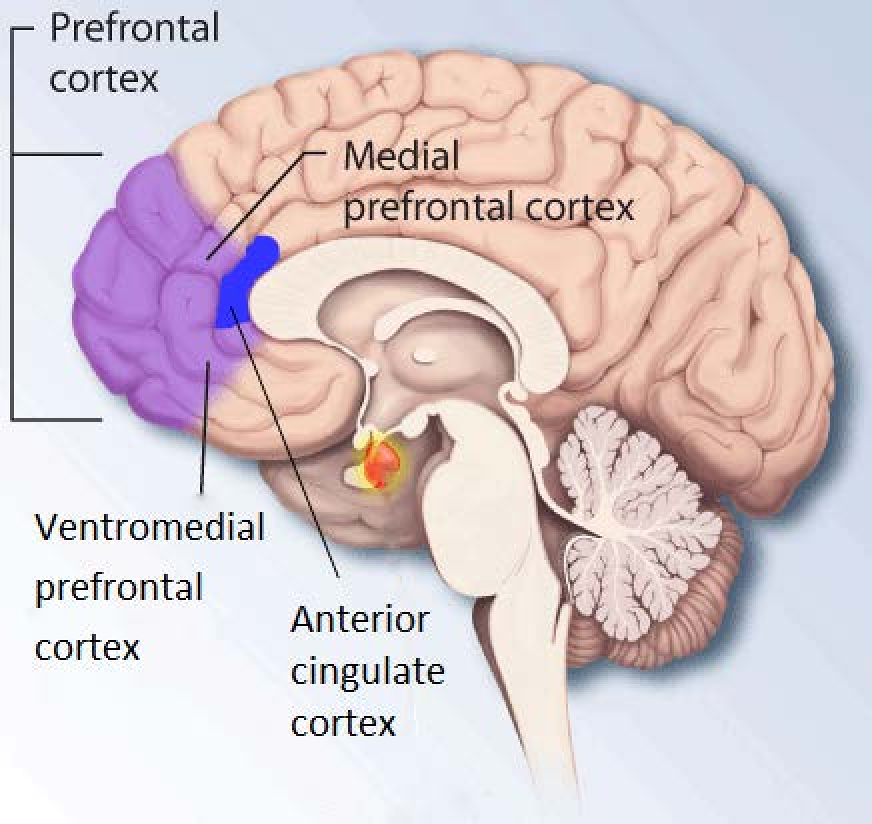


Figure 1.2. Diagram of the brain showing the location of the anterior cingulate cortex in the prefrontal cortex. Modified image, original from Wikimedia Commons.

The ERN is elicited regardless of error awareness (Endrass et al., 2005; Klein et al., 2007; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001) as research has shown that error awareness is dissociable from the ERN (Di Gregorio, Steinhauser, & Maier, 2016). Some studies have investigated the relationship between neural and behavioural responses to errors; however the relationship between the ERN and post-error slowing is controversial. Some research has shown a positive correlation between ERN amplitude and post-error slowing (Debener et al., 2005; Gehring et al., 1993; Rodríguez-Fornells, Kurzbuch, & Münte, 2002) while other studies have not found this correlation (Dudschig & Jentzsch, 2009; Gehring & Fencsik, 2001; Hajcak et al., 2003). The relationship between post-error slowing and the ERN could also depend on type and priority of the task, as post-error slowing is often observed following an error, but not as consistently as the ERN.

The ERN is followed by the error positivity (Pe, see Figure 1.1) that peaks around 200 to 500 ms following error onset and has an early and late component (for a review, see Gehring et al., 2012; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). The early Pe shows a fronto-central scalp distribution, much like the ERN, whereas the late Pe shows a centro-parietal distribution. The Pe is correlated with error awareness, with consistently larger Pe amplitudes when participants are aware they have made an error than when they are unaware (Godefroid, Pourtois, & Wiersema, 2016; Hewig, Coles, Trippe, Hecht, & Miltner, 2011; Murphy, Robertson, Allen, Hester, & O'Connell, 2012; Nieuwenhuis et al., 2001).

A third error-related component is the feedback-related negativity (FRN, see Figure 1.3). The FRN is a negative component that peaks approximately 250 ms after feedback and has a fronto-central topography (Gehring et al., 2012; Miltner, Braun, & Coles, 1997). The FRN is elicited upon error confirmation when correctness of the response is only available through external feedback. For example, if someone guesses at a difficult true/false question and the guess was incorrect, external feedback is the first indication that an error was made. This can be applied to a motor task as well, such as throwing a dart at a distant target. FRN amplitude has been shown to scale with reward prediction error (i.e., the discrepancy between predicted and experienced action outcome) and is negatively correlated with unexpected outcomes (Chase, Swainson, Durham, Benham, & Cools, 2011; Holroyd & Coles, 2002; Holroyd & Krigolson, 2007; Nieuwenhuis, Holroyd, Mol, & Coles, 2004). However, some studies demonstrate that amplitude of the FRN is only affected by the valence of the outcome (i.e., right or wrong) and that the degree of prediction error is reflected by the P300 component, which generally follows the FRN (Holroyd, Hajcak, & Larsen, 2006; Philiastides, Biele, Vavatzanidis, Kazzer, & Heekeren, 2010; Ullsperger, Danielmeier, et al., 2014; Ullsperger, Fischer, Nigbur, & Endrass, 2014; Yeung & Sanfey, 2004).

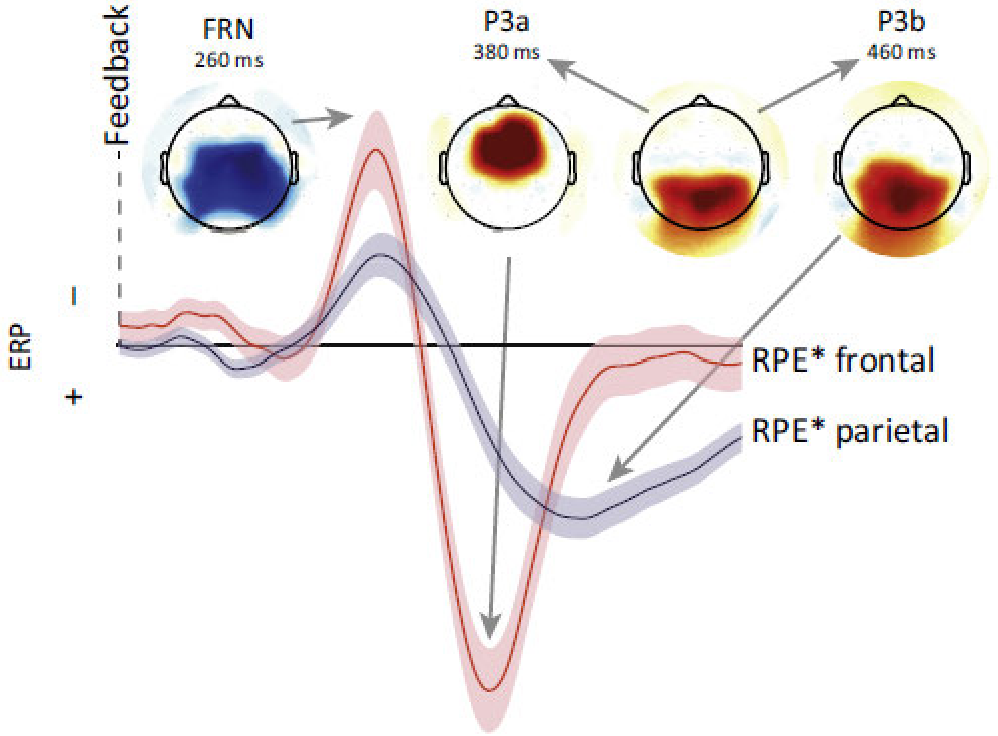


Figure 1.3. Latencies and topographies of the feedback-related negativity (FRN) and P3 components. The P3 component is thought to scale with magnitude of reward prediction error. From Ullsperger, Fischer, et al. (2014).

1.1.3 Theoretical Accounts of Error Processing

Theoretical accounts of error processing suggest that monitoring is achieved through both forward and inverse internal models (Lutz, Puorger, Cheetham, & Jancke, 2013; Wolpert, Ghahramani, & Jordan, 1995; Wolpert & Kawato, 1998; Wolpert, Miall, & Kawato, 1998). Forward models predict the sensory consequences of an action by using an efference copy of the motor commands as the action is being performed (David, Newen, & Vogeley, 2008; Pacherie, 2008; Wolpert et al., 1995). This efference copy is used to run an internal simulation of the process of action execution. The prediction becomes more accurate through learned associations, such as those resulting from extensive training of a particular action. Inverse models compute the motor commands required to achieve a certain action given the current environment (Pacherie, 2008; Wolpert et al., 1995). Forward and inverse models work in a complementary fashion, using a series of comparators to update the models as the motor commands are executed (see Figure 1.4). The predictions from the models can then be updated as the action is being executed. Internal models are at the core of theories about error processing and performance monitoring. The main theories explaining error processing are the error detection theory, the conflict monitoring theory, and the reinforcement learning theory.

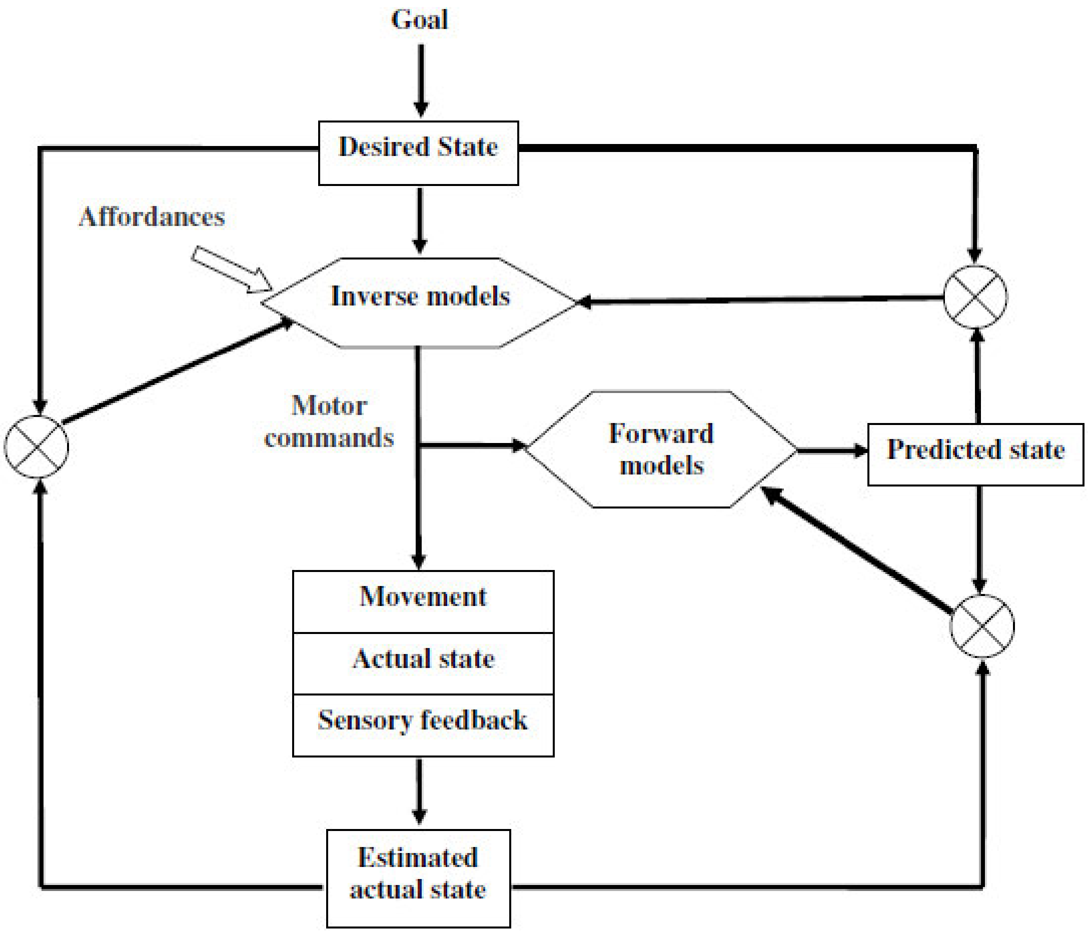


Figure 1.4. Components of motor control system. Forward and inverse models work together and use comparators to update predictions within the context of performance monitoring and error processing. From Pacherie (2008).

The error detection theory suggests that the ERN represents a process of comparison between the motor system output and the best estimate of the correct response at the time of the ERN (Falkenstein et al., 1991; Gehring et al., 2012). This comparison relies on the efference copy of the motor command. In speeded reaction-time tasks, an error often occurs because the response is executed before the stimulus has been completely processed. As stimulus evaluation progresses, a forward model uses the efference copy of the motor command and compares it with the estimate of the correct response. This estimate is now more informed and may be different from the estimate at the time the motor command was initiated. The prediction is constantly updated as new information becomes available (i.e., as the stimulus is more fully processed), however once the motor command is initiated, it cannot be altered. Thus, a discrepancy between the estimate and motor command efference copy arises and an error signal is generated, reflected by the ERN and, behaviourally, in post-error slowing (Coles, Scheffers, & Holroyd, 2001; Falkenstein et al., 1991; Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Gehring et al., 1993; Ullsperger & von Cramon, 2001). In addition, a study using altered feedback showed that altered feedback in simple piano melodies increased the estimate of errors committed (Pfordresher & Beasley, 2014). In this experiment, the participants were non-musicians and thus would not be as familiar as musicians with receiving finger-piano key tactile information as feedback. Therefore, the tactile information of playing a correct note may be overridden by hearing altered feedback, as that is a more familiar source of information. This suggests that the efference copy can be updated on the basis of information from different modalities and can be influenced by experience.

The error detection theory has been used to explain the FRN as well (Miltner et al., 1997). A mismatch arises from the comparison of the efference copy and the feedback of the actual achieved outcome (Ullsperger, Danielmeier, et al., 2014). This expansion of the error detection theory to include the FRN assumes that the FRN and ERN are functionally equivalent, supported by research showing the ERN and FRN are both generated in the posterior medial frontal cortex (Ullsperger, Danielmeier, et al., 2014). However, arguments against this theory point out that for this to be a plausible explanation, the network involved in generating the ERN would require access to information about the correct response (Carter et al., 1998).

The conflict monitoring theory addressed this discrepancy by positing that the ERN reflects conflict between multiple competing responses (Carter et al., 1998). It is suggested that this conflict signal enacts adjustments (i.e., post-error slowing) after the conflict, in order to reduce conflict in upcoming responses (for a review, see Botvinick, Cohen, & Carter, 2004). The activation of competing motor responses creates conflict. A strong correct response tendency can override the conflict, resulting in pre-response conflict and a correct response. However, if an error response is executed, the continued processing of stimuli reinforces the conflict and the ERN is elicited, along with post-error slowing (Ullsperger, Danielmeier, et al., 2014). Support for the conflict monitoring theory comes from several studies showing activity in the posterior medial frontal cortex during response conflict (Barch, Braver, Sabb, & Noll, 2000; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Braver, Barch, Gray, Molfese, & Snyder, 2001; Carter et al., 1998; Kerns et al., 2004; Ridderinkhof et al., 2004; Ullsperger & von Cramon, 2001; van Veen & Carter, 2002a; Weissman, Giesbrecht, Song, Mangun, & Woldorff, 2003).

However, there is evidence that although error processing and conflict monitoring activate some overlapping cortical areas, they are distinct processes. For example, the posterior medial frontal cortex is active during feedback without activation of the motor response, a pattern that the conflict monitoring theory does not account for (Ullsperger, Danielmeier, et al., 2014). In addition, a study looking at the ERN by degree of conflict measured the amount of temporal overlap between correct and incorrect response activations (Burle, Roger, Allain, Vidal, & Hasbroucq, 2008). The authors found that conflict increased as temporal overlap increased, but ERN amplitude decreased as temporal overlap increased. From this, they concluded that the anterior cingulate cortex is not involved in conflict monitoring (Burle et al., 2008). A study using simultaneous EEG and fMRI recordings showed a dissociation between conflict monitoring and error processing (Iannaccone et al., 2015). ERN activity was associated with activation of the anterior cingulate cortex, the rostral cingulate zone, and the pre-supplementary motor area, whereas the N2 (a component related to conflict monitoring) was associated with increased activity in the pre-supplementary motor area only.

Further, fMRI research has provided evidence of a dissociation between response conflict monitoring and error processing (Garavan, Ross, Kaufman, & Stein, 2003). The researchers manipulated response conflict and showed activation in the anterior cingulate cortex only for error processing and activation in the pre-supplementary motor area sensitive to response conflict. Overlapping activation between response conflict and error processing was found in the caudal cingulate cortex (Garavan et al., 2003). Additional fMRI research supports the dissociation. Common activation associated with errors with and without response conflict included the dorsal anterior cingulate cortex, the medial superior frontal cortex, and the bilateral inferior frontal gyrus (Wittfoth, Küstermann, Fahle, & Herrmann, 2008). Errors with response conflict were additionally associated with activation in the rostral anterior cingulate cortex and precuneus, whereas errors free of response conflict were additionally associated with activation in the right inferior parietal cortex (Wittfoth et al., 2008). Taken together, these findings suggest that while there is some overlap in neural activity of response conflict monitoring and error processing, there are still elements to error processing that are not accounted for by conflict monitoring and there is evidence of a dissociation between these processes.

A third theory is the reinforcement learning theory. The reinforcement learning theory is based on reward prediction error and a reduction of midbrain dopamine firing upon negative feedback (Ullsperger, Danielmeier, et al., 2014). This theory addresses the role of several areas of the brain, including the anterior cingulate cortex (which includes the anterior midcingulate cortex), basal ganglia, amygdalae, and the dorsolateral and orbitofrontal cortices (Holroyd & Coles, 2002). The anterior cingulate cortex acts as a motor control filter, choosing which from several potential motor responses will be passed on to the motor system, leading to the actual response. An error response will occur when the motor response leads to an outcome that is worse than predicted, reflected by the ERN and behaviourally by post-error slowing. This theory posits that the basal ganglia are responsible for monitoring responses and comparing actual responses with predicted ones. The actual responses can be either better or worse than predicted, with an error being worse than predicted. The error (or negative feedback) is registered by the basal ganglia and results in a decrease in dopaminergic activity. This leads to a disinhibition of neurons in the anterior cingulate cortex and triggers the ERN. In contrast, a correct response leads to an increase in dopaminergic activity. In this way, the anterior cingulate cortex is trained by these error signals and reinforces the correct motor response, thus reducing the chance of sending through an incorrect motor response. The reinforcement learning theory can also account for the FRN, as studies have provided evidence that the FRN reflects reward prediction error (Fischer & Ullsperger, 2013; Rutledge, Dean, Caplin, & Glimcher, 2010; Talmi, Fuentemilla, Litvak, Duzel, & Dolan, 2012).

A further aspect of the reinforcement learning theory is the first indicator hypothesis. This hypothesis suggests that an error signal is elicited by the earliest available information that indicates the outcome of an action is worse than predicted (Holroyd & Coles, 2002; Stahl, 2010). Thus, the ERN is elicited by the actual error response and any further feedback about the error is redundant. For example, if someone drops a glass of water, they do not need to hear the smashing of the glass on the floor to know that an error has occurred. However, if knowledge about the correctness of a response is only available through feedback, then the FRN would be elicited upon error confirmation, as the feedback is the first indication of the error. For example, if someone guessed at a difficult true/false question, the feedback is the first indication that an error was made if the person guessed wrong. This theory suggests that the ERN and FRN represent the same cognitive mechanism, but at a different time course and with a different reference (error response for the ERN, feedback for the FRN).

Research suggests that the formation of an internal model can shift an actor's reliance on external feedback to the error response (Lutz et al., 2013). Musically untrained participants learned to match certain auditory pitches with specific key presses on a piano keyboard by playing the appropriate key to reproduce a target pitch. EEG activity was recorded throughout, with specific interest in how the activity changed in response to performed errors and altered feedback before and after training. Results indicated an increase in ERN amplitude with the development of the internal model. That is to say, ERN amplitude for performed errors increased as participants learned the mapping between auditory pitch and key presses. Amplitude of the FRN remained stable throughout the experiment, regardless of whether the error was committed by the participant or by the altered feedback. This suggests that the development of an internal model can change the reference point for error processing (i.e., from feedback to error response) and also reduce the time it takes for the performance monitoring system to process the error.

1.1.4 Errors and Sequential Tasks

The conflicting evidence in support of the different theories of error processing may be due to the variety of tasks and types of tasks involved in the research. Many studies involving error monitoring and processing involve discrete tasks, such as go/no-go tasks, the Stroop task, flanker tasks, and other speeded reaction-time tasks. However, some studies have looked at error monitoring in sequential tasks, such as typing and piano performance. Discrete tasks involve responding to an external stimulus. A stimulus is presented, the response is made, another stimulus is presented, and so on. While there may be carry-over effects from one trial to the next, there is generally no intended connection from one trial to the next and one response only requires one motor command. In sequential tasks, multiple responses are being generated continuously and in a specific pattern. For example, with typing, the responses (i.e., the letters typed) need to be in a specific order for the output to make sense. Likewise, in piano performance, the piano keys need to be played in a specific order to accurately perform the piece or exercise. Furthermore, when responses are performed by different fingers, there is temporal overlap in responses. That is, during typing and piano performance, a second action is already initiated before the first action is completed, provided the actions are being performed by different fingers (Soechting & Flanders, 1992).

Responses in discrete tasks are externally guided – they are generated in response to a target stimulus. In sequential tasks, responses can be externally or internally prompted (Keller et al., 2006). For typing, externally guided responses would be, for example, typing out written notes into a computer document, whereas internally guided responses could consist of typing an email to a friend. In piano performance, externally guided responses would involve playing from a score, whereas internally guided responses would involve playing from memory or improvising. EEG and fMRI research shows that externally prompted responses elicit different neural activation (Keller et al., 2006) and recruit different cortical areas (Debaere, Wenderoth, Sunaert, Van Hecke, & Swinnen, 2003; Gowen & Miall, 2007) compared to internally prompted responses. However, even in sequential tasks, there can be some combination of external and internal influence on responses. When playing from a score (an externally guided response), a musician still relies on an internal sense of timing for the pace of playing and internal knowledge guiding expressive interpretation. When playing a piece from memory or improvising (an internally guided response), a musician may be playing with other performers and have to adjust timing during performance to match the externally directed timing.

Findings in error processing in sequential tasks show a slightly different pattern of results than in discrete tasks. As discussed previously, in discrete actions, pre-error and error responses are faster than pre-correct and correct responses (Danielmeier & Ullsperger, 2011). The error response is then followed by a slower post-error response. This is generally thought to reflect the speed-accuracy trade-off, however some research shows that accuracy actually decreases after an error (Houtman & Notebaert, 2013; Rabbitt & Rodgers, 1977). In contrast, sequential tasks show evidence for pre-error slowing, error slowing, and post-error slowing (Kalfaoğlu & Stafford, 2014; Maidhof et al., 2009; Ruiz et al., 2009; Shaffer, 1975). Additionally, error responses are performed with less movement force than correct responses (Maidhof et al., 2013; Maidhof et al., 2009; Rabbitt, 1978; Ruiz et al., 2009).

EEG findings for errors in sequential tasks are similar to those in discrete tasks, with some notable differences. In piano performance, researchers observed an ERP that peaked approximately 50 ms before error onset, the pre-ERN (Maidhof et al., 2009; Ruiz et al., 2009). This component peaks prior to the onset of pitch errors and has a fronto-central topography. It is elicited regardless of the presence of auditory feedback – the pre-ERN for pitch errors was observed when pianists could not hear their performance, as participants played on an electric piano with the sound turned off during one condition (Ruiz et al., 2009). In typing, the negative component is also observed prior to the onset of the error for both corrected and uncorrected errors (Kalfaoğlu et al., 2018). In both of these types of sequential tasks, the negative component is followed by the Pe (Kalfaoğlu et al., 2018; Maidhof et al., 2009; Ruiz et al., 2009).

In the studies reviewed above, one difference between these sequential studies and discrete studies is the expertise of the participants. Participants in the piano experiments were expert pianists who were familiar with the feel of a piano, the different notes, and the relation of their body movements to the piano (i.e., tactile and proprioceptive feedback; Maidhof et al., 2009; Ruiz et al., 2009). Likewise, participants in the typing experiments were expert touch typists who were familiar with the tactile feedback of a keyboard and the location of the letters on the keyboard (Kalfaoğlu & Stafford, 2014; Kalfaoğlu et al., 2018). This expertise with the instruments and the regularity with which experts rehearse is related to increases in cortical areas involved in action planning (Yang, 2015), allowing experts to process errors very quickly. In contrast, research using discrete tasks investigates error effects in non-expert populations, with people who have little to no experience with the task they are performing.

Moreover, responses to errors changes over the course of skill training (Padrão, Penhune, de Diego-Balaguer, Marco-Pallares, & Rodriguez-Fornells, 2014). This study investigated learning to synchronise with rhythmic sequences and showed that errors performed by participants before training elicited an ERN with a larger amplitude than those committed after training (Padrão et al., 2014). The amplitude of the Pe component increased after training. The authors suggested that the larger amplitude of the ERN before training may be attributed to greater response conflict in the motor system. However, as previously mentioned, when learning auditory pitch and key press pairings, errors from incorrect key presses elicited ERNs with increased amplitude after training compared to before training (Lutz et al., 2013). These differences could be because of the task involved. In the synchronising task, participants would already have an internal model of what the two synchronised parts would sound like together. Further, synchronisation is a general task performed in daily life (e.g., tapping along to a song). However, in the piano task, the internal model of auditory-key press pairings did not exist prior to the experiment. The experience and training throughout the experiment formed the internal model. Thus, the internal model can be updated or improved with the new information from the task (Pacherie, 2008). Further, while Padrão et al. (2014) attribute the differences in ERN amplitude to response conflict, Lutz et al. (2013) specifically kept the number of responses constant in order to reduce response conflict.

Another difference between sequential and discrete tasks is the degree of ecological naturalness. Ecological validity is concerned with balancing the relationship between real world phenomena and the exploration of these phenomena in experimental settings (Schmuckler, 2001). According to Schmuckler (2001), the dimensions involved in ecological validity are the nature of the research setting or context, the nature of the stimuli, and the nature of the task, behaviour, or response. In the sequential tasks reviewed above, the experiments have focused on piano playing and typing – actions that are performed regularly by the participants with stimuli that is in a familiar format (i.e., notated piano music for pianists and typed documents for typing). Thus, in these experiments, the nature of the stimuli and the nature of the task maintain high ecological validity. In experiments using discrete tasks, the tasks are reaction time button-press tasks in which participants are interacting with unfamiliar stimuli. Stimuli in discrete tasks are often repetitive and monotonous and participants' attention and effort can drift

(Ruiz, Strübing, Jabusch, & Altenmüller, 2011), whereas stimuli in sequential tasks (especially involving music) are complex and dynamic.

Thus, responses to errors differ depending on the type of task performed and skill level of the performer. Errors during discrete tasks are preceded by speeding, followed by post-error slowing, and elicit the ERN followed by the Pe. On the other hand, errors during sequential tasks are preceded and followed by slowing, and elicit an ERN that peaks prior to the onset of the error, followed by the Pe. The differences in latencies between the ERN components in different types of tasks may be attributable to the expertise of the performers. Music performance is an ideal task in which to study error processing as it is high in ecological validity.

1.2 Joint Action

Joint action is a social interaction between at least two people, occurring in space and time, to bring about change in the environment (Sebanz, Bekkering, & Knoblich, 2006). Cooperative activity is facilitated by joint action. Moving a heavy or large object, playing team sports, or dancing with a partner are all cooperative activities, and the progress to the overall goals of these activities depends on joint action. This is particularly relevant for actions in which synchronous joint action is necessary for the shared goals to be achieved, such as dance and musical performance.

Expert joint action seems effortless; however, anyone who has played in a band, sang in a choir, or danced in a group knows synchronous joint action takes hours of practice, both individually and with the co-performers. Joint action is so demanding because it requires attention to one's own part as well as the overall shared goals of the activity (Keller, Novembre, & Hove, 2014; Novembre & Keller, 2014). As will be discussed below, it is beneficial to have an understanding of partners' parts, as that can facilitate coordination and synchronisation. Joint action also increases the potential for errors, as there is an additional source of possible error. As a general example, consider rowing a boat. If the rowers are acting together and rowing in synchrony, they will progress toward their destination. However, if any rower starts rowing a bit slower or faster than the others, it will make the boat go off course, disrupting progress to the destination. In a music ensemble, one musician could start playing slightly faster than the rest of the group; another performer may play an incorrect note. Both of these errors affect the shared goal of error-free performance. Any error made by one performer affects whether the shared goals are met. In this section, I will discuss the mechanisms that support joint action, errors committed during joint action, and how music has been used to investigate joint action.

1.2.1 Mechanisms Facilitating Joint Action

Joint action requires certain abilities to be successful, including shared representation of tasks and goals (or co-representation), action prediction, and integration of the predicted outcomes of own with other's actions (Sebanz, Bekkering, et al., 2006). It has been proposed that these abilities are facilitated by action simulation, common coding, and internal models.

1.2.1.1 Co-representation

There is consistent and growing evidence supporting the role of co-representation in joint action tasks. Co-representation is the hypothesis that co-acting partners internally represent their partner's task and that representation is integrated into the actor's own action planning (Bekkering et al., 2009; Newman-Norlund, van Schie, van Zuijlen, & Bekkering, 2007). Research has shown that partners may not necessarily co-represent exactly what their partner is doing, but at least must co-represent that the partner is responsible for certain parts of the task and when the actor and the partner must act (Wenke et al., 2011). Co-representation assumes a shared perceptual understanding in which the actions will occur (Sebanz, Bekkering, et al., 2006). Thus, co-representation is facilitated by joint attention. Attending to and perceiving the same events and environment allows partners to work together and communicate more effectively about their actions (Böckler, Knoblich, & Sebanz, 2012; Richardson & Dale, 2005; Wu, Pan, Su, & Gros-Louis, 2013). Further, partners who cannot attend to the same events and environment take longer to complete a cooperative task and are more prone to errors (Clark & Krych, 2004).

There is evidence that co-representation helps with prediction of a partner's actions, enabling accurate timing of initiating one's own actions (Kourtis, Sebanz, & Knoblich, 2013). This evidence comes from research exploring a slow, negative component – the contingent negative variation (CNV). The CNV is a component that shows continuous development during the time period between informative stimuli and imperative stimuli, peaking around action onset (Walter, Cooper, Aldridge, McCallum, & Winter, 1964), and is thought to reflect time-based motor response preparation (for a review, see Leuthold, Sommer, & Ulrich, 2004; Van Rijn, Kononowicz, Meck, Ng, & Penney, 2011). An EEG study using a joint action giving/receiving object task found that the CNV reached its maximum amplitude when a partner initiated the giving action, even though the CNV usually peaks at onset of one's own action (Kourtis et al., 2013). The authors suggested their results indicate that the partner's task was accurately represented, allowing for accurate prediction and leading to precise timing of initiating one's own action to receive the object.

Although some research suggests co-representation can occur almost automatically (Sebanz, Bekkering, et al., 2006), this may not be the case in competitive situations where it may be less beneficial to represent a competitor's task (de Bruijn, Miedl, & Bekkering, 2008). De Bruijn and colleagues (2008) showed that successful competitive performance in a go/no-go task involved a reduction of co-representation, either by not representing the competitor's task or by inhibiting that representation. Unsuccessful competitive performance was related to increased co-representation. The researchers speculated that increased co-representation may be due to personality traits such as higher empathy. Further, their results demonstrate that co-representation is not completely automatic. Thus when acting together, co-representation is increased by shared attention and allows for better coordination, but may detract from performance during some competitive tasks.

1.2.1.2 Action Prediction

Action prediction is necessary in order to coordinate fluently with others. If a partner waits to observe the action of another before planning their own actions, coordination may be compromised. Predicting a partner's actions allows for appropriate timing and execution of complementary actions (Sebanz, Bekkering, et al., 2006). There is evidence that prediction of others' actions is based on one's own behavioural repertoire (Newman-Norlund, Bosga, Meulenbroek, & Bekkering, 2008; Welsh, Wong, & Chandrasekharan, 2013). People are more successful in joint action when performing identical actions than when performing complementary actions, suggesting that partners are better able to predict the outcomes of a partner's action when performing the same action oneself (Newman-Norlund et al., 2008). Likewise, people asked to judge other's action abilities base those judgements on what they consider their own abilities to be and only take the actor's abilities into account when specifically instructed to do so (Welsh et al., 2013). Welsh and colleagues (2013) showed participants videos of adults and children moving their index finger between two targets and different distances and asked to judge if it was possible for to move accurately at the shown speed. Participants based those judgements on their own ability to move at the shown speed, except when they were specifically instructed to consider if the actor could move accurately at that speed.

Prediction based on one's own performance and abilities affects coordination as well. Musicians who are familiar with a partner's part, but not their partner's playing style, demonstrate decreased coordination with their partner, suggesting that predictions of timing were based on the performer's own playing style instead of taking into account the partner's abilities (Ragert, Schroeder, & Keller, 2013). The judgement of a partner's action abilities is likely an adaptable judgement though, as familiarity with the partner will lead to more accurate judgements about their abilities. For example, people are more skilled at identifying their own actions than the actions of others (Keller, Knoblich, & Repp, 2007; Knoblich & Flach, 2003; Loula, Prasad, Harber, & Shiffrar, 2005; Repp & Knoblich, 2004), and people are better at recognising actions of a friend than the actions of a stranger (Loula et al., 2005). Additionally, neural activity is stronger in the anterior cingulate cortex when people observe errors made by a friend compared to observing errors made by a stranger, as indexed by increased amplitude in the FRN component when observing errors (Kang, Hirsh, & Chasteen, 2010).

Familiarity with the task increases the ability to simulate and predict action outcomes. Thus, experts have an advantage when observing actions of another as they recruit motor areas of the brain when simply observing actions that fall under their expertise (Bangert et al., 2006; Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005; Calvo-Merino, Grèzes, Glaser, Passingham, & Haggard, 2006). For example, basketball experts are significantly better than novices at predicting the actions of another player (Abreu et al., 2012; Aglioti, Cesari, Romani, & Urgesi, 2008; Sebanz & Shiffrar, 2009). fMRI research has shown that there is significantly more hemodynamic activity in the motor areas of the brain when dancers observe actions they have expertise in producing (i.e., in their own style of dance) compared to actions they do not have experience producing (i.e., in another style; Calvo-Merino et al., 2005). A subsequent study investigated the difference in cortical activation when a ballet dancer observed a partner's actions compared to observing actions that the dancer performed regularly (Calvo-Merino et al., 2006). As some ballet moves are only performed by one sex, both partners had similar visual exposure to both sets of actions, but only motor experience with one set of actions. The fMRI results showed stronger blood-oxygen dependency levels in the action observation-action execution network when the dancers were observing the set of actions they had experience performing compared to those they only had visual exposure to.

Similar results have been reported in music research with novices (Lahav, Saltzman, & Schlaug, 2007). Non-musicians were trained to perform a piece of music by ear. After training, participants listened to the trained piece, the practiced notes in a different order, and auditorily-familiar but motorically unfamiliar music while fMRI activity was measured. When listening to the trained piece, participants showed activation in motor-related areas, specifically in areas that have been associated with action observation (i.e., Broca's area, the premotor region, intraparietal sulcus, and inferior parietal region). Listening to the practiced notes in a different order also activated this network, although to a lesser degree, whereas listening to the untrained music did not activate this network. This suggests that having previously performed an action gives greater ability to simulate that action and, in turn, better ability to predict an outcome involving that action. The increased ability to predict outcomes due to expertise or previous performance may lead to increased error processing and error monitoring for both own and other's actions, as will be discussed further in the section on joint action and errors.

1.2.1.3 Integration of Predicted Outcomes

Integration of predicted outcomes of both own and another's actions is important within joint action. Partners must plan and act depending on what they predict the other will do, and these predictions must be factored in to the action plan. This integration allows for an estimate of whether the shared goal will be achieved. Further, research on action observation has revealed that one's own and others' actions may be represented using the same neural resources, through the action observation-action execution network (for a review, see Rizzolatti & Sinigaglia, 2010). This network comprises the inferior precentral gyrus, the posterior part of the interior frontal gyrus, and the inferior parietal lobule (Rizzolatti & Craighero, 2004). This could allow for a readiness for co-operative activity and integration of a partner's actions. As discussed in the previous section, simply observing an action elicits activity in the same areas as producing that action, and that may enable prediction and initiation of motor commands based on those predictions.

There is evidence that integration of predicted outcomes occurs automatically and this integration is reflected in behaviour. A study involving imagination showed that even the imagined actions of a partner are reflected in one's own imagined actions (Vesper, Knoblich, & Sebanz, 2014). Participants judged the timing of their own solo imagined jumps and imagined jumps that required timing the landing with an imagined partner. When the imagined partner's jump was longer than their own, participants factored that into their judgement of when they would land. Research has demonstrated that a partner's actions are integrated into one's own performance even when that performance does not require taking the partner's actions into account (Sebanz, Bekkering, et al., 2006; Sebanz, Knoblich, & Prinz, 2003, 2005), including when instructed not to coordinate (R. C. Schmidt & O'Brien, 1997). Even in competitive contexts, when representing a partner's task is often detrimental to one's own performance, people are similarly prone to representing their partner's task (Sebanz, Knoblich, Prinz, & Wascher, 2006). Taken together, this research demonstrates that, even when a partner's actions are irrelevant or detrimental to one's own task, one still forms an automatic representation of the partner's actions.

Integration of another's actions or predicted actions also assumes the segregation of actions and predicted actions between the self and other. Research shows that alpha oscillations are involved in balancing the integration and segregation of self and other actions and predictions (Novembre, Sammler, & Keller, 2016). Pairs of pianists played short musical excerpts together while action familiarity and synchronisation were manipulated. High synchronisation was associated with self-other integration, as indexed by the suppression of alpha oscillations, whereas low synchronisation was associated with self-other segregation, as indexed by enhancement of alpha oscillations. Thus, integration of own and other's parts is necessary to act in coordination and to make accurate predictions about both partner's actions. Segregation is also necessary to maintain self-other distinction and predictions about each partner's individual role in the joint action.

1.2.1.4 Underlying Supporting Processes

The mechanisms supporting joint action rely on related underlying functional processes, neuroanatomical structures, and computational concepts – action simulation, the action observation-action execution network, and internal models. In this section, these substrates will be addressed with respect to their roles in supporting joint action.

Action Simulation

Action simulation is the process by which motor areas in the brain are activated in a similar way as when an action is produced, but without any overt movement (Decety & Grèzes, 2006; Keller, 2012). Simulation facilitates co-representation through internal models by which the model estimates and predicts the action outcome from the motor command and perceptual cues from the senses and the environment (Keller, 2012; Schubotz, 2007). Neuroimaging research supports the idea of simulation, as fMRI studies have found similar patterns of cortical activation during action execution and action observation in areas including the premotor and parietal cortices (for a review, see Sebanz & Knoblich, 2009).

Simulation facilitates not only co-representation, but also supports action prediction. As discussed above, prediction of others' actions is facilitated through simulation of those actions. These simulations are based on one's own behavioural repertoire (Ragert et al., 2013; Welsh et al., 2013). Prediction accuracy increases when the simulated action is motorically familiar (i.e., the action has been performed previously; Lahav et al., 2007; Stapel, Hunnius, Meyer, & Bekkering, 2016). Further, when performing a joint action, simulation of a partner's action is more accurate if the other person has previously performed that action, as seen in research in sports (Abreu et al., 2012; Aglioti et al., 2008), dance (Calvo-Merino et al., 2005; Calvo-Merino et al., 2006), and music (Bangert et al., 2006; Lahav et al., 2007).

Finally, simulation is used to help integrate a partner's actions with one's own actions. This has been observed in studies about jumping with a partner or an imagined partner (Vesper et al., 2014; Vesper, van der Wel, Knoblich, & Sebanz, 2013). When imagining landing a jump at the same time as an imagined partner, participants timed the imagined jump differently depending on the abilities of the imagined partner. This suggests that the imagined partner's actions were integrated into the simulation of the participant's own imagined jump (Vesper et al., 2014).

Action Observation-Action Execution Network

Research on the action observation-action execution network demonstrates that observing actions activates the same neural areas required for producing those actions (for a review, see Rizzolatti & Craighero, 2004).

This network is formed by two main regions in the brain – the inferior precentral gyrus and posterior part of the inferior frontal gyrus, and the inferior parietal lobule, including the cortex inside the intraparietal sulcus (Rizzolatti & Craighero, 2004; Rizzolatti & Sinigaglia, 2010). The ideomotor theory suggests that there is a common neural coding between perceived events and intended actions (for a review, see Shin, Proctor, & Capaldi, 2010; Tsai, Kuo, Jing, Hung, & Tzeng, 2006).

The action observation-action execution network facilitates co-representation and prediction as it enables simulation. The overlap of neural activation for perceiving and performing actions allows for more accurate prediction of one's own actions and for better prediction of another's actions (Newman-Norlund, Noordzij, Meulenbroek, & Bekkering, 2007). If you have never performed a specific action, it is difficult to predict how successful that action will be or to perform that action with a partner. However, performance and prediction can improve quickly once an action has been executed a few times.

The action observation-action execution network also enables integration of multiple parts. This idea is supported by evidence that people tend to represent another's part even when it is more effective to only represent their own part (Sebanz et al., 2005). By activating motor areas of the brain during action observation, the motor plan can integrate those observed actions into the motor command. In this way, the motor command has accounted for the actions of another and is primed to execute the action at the right time. The action observation-action execution network seems tailored to integration, as there is more activation in the network during complementary action compared to imitative action (Newman-Norlund, van Schie, et al., 2007). Thus, integration supported by the action observation-action execution network may facilitate the execution of complementary actions and help adapt the motor response to ongoing observed actions (Colling, Knoblich, & Sebanz, 2013).

Internal Models

As discussed earlier, internal models use an efference copy of the motor commands to simulate and predict the outcome of an action as it is being performed. The internal model and its predictions are updated as new information is provided. Together, the simulation and integration of different parts by internal models enables more accurate prediction and timing for actions that involve an acting partner. Internal models allow for integration of self and other's actions. Internal models are not only used to predict one's own behaviour, but also the behaviour of a partner (Keller, Novembre, & Loehr, 2016; Wolpert et al., 1995). Internal models are used in models of joint action to explain how both co-actors represent their own and their partners' parts.

1.2.2 Models of Joint Action

A joint action model based on music ensemble performance includes a more detailed account of the role of internal models in joint action (Keller et al., 2016). As explained by Keller et al. (2016) and shown in Figure 1.5, during joint action there is ongoing prediction and estimation of both self and other parts. This model of joint action shows the cognitive processes of one actor (i.e., the self), depicting predicted and estimated states for the self and a co-acting partner (i.e., the other).

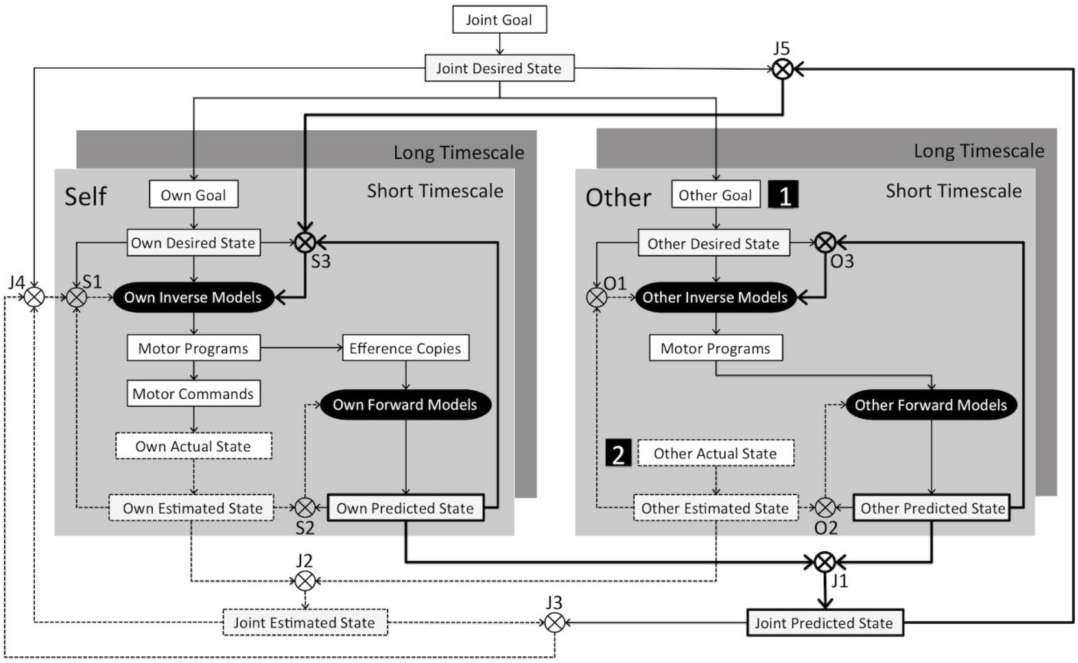


Figure 1.5. Model of joint action, showing how self and other inverse and forward models work together during joint action, from the perspective of the self. Dotted lines indicate the use of sensory feedback, solid lines indicate feedforward processes. From Keller et al. (2016).

The model is driven by the self's understanding of the joint goal, which contributes to bringing about the joint desired state. The self goal is based on the joint desired state. For example, if two pianists are playing together, one pianist may be planning to play a series of keystrokes to achieve the joint goal of performing a synchronized piece with two voices. The self goal brings about the self desired state. Self inverse and forward models facilitate online action planning and motor control for one's own performance in order to bring about the self desired state. The self inverse models generate motor programs to achieve the action goals, attempting to minimize errors or discrepancies (S1 in Figure 1.5) between the desired state and estimates of the actual state resulting from the motor commands that will be carried out. From the example, the self inverse models will generate the finger movements to specific piano keys and timing to match the rhythm and pace needed for the performance. The self inverse model generates an efference copy that is used by the self forward model to predict the end state of the motor plan. In the case of sequential actions like the piano example, this is an ongoing prediction that is continuously updated with sensory feedback information. The self inverse model generates the self estimated state based on the self actual state. The self estimated state is then compared to the self predicted state generated by the self forward model (S2 in Figure 1.5). A mismatch or discrepancy between the self estimated and self predicted states triggers compensatory measures. In the piano example, the series of piano keystrokes is planned out, with the self inverse model generating the motor programs and motor commands to play the correct keys at the proper time, according to the overall joint goal. The pianist's own movements and actions are monitored throughout and an estimated state is generated through the inverse models based on the movements and actions being monitored. A copy of the motor programs is sent to the self forward models to generate a prediction of the performance. The estimated state and predicted states are compared to identify any discrepancies. Are the piano keys played in the predicted order? Are the keys being played at the expected time? Am I playing too loudly or too softly?

Depending on these comparisons, the pianist can make adjustments during the performance to get closer to achieving the joint goal. With increased training and experience, self forward models become more efficient at detecting errors and potential errors, allowing for error avoidance during action execution. In this way, there can be a comparison between the desired state and predicted state (S3 in Figure 1.5). Depending on the time scale, some discrepancies between these states can be addressed prior to execution of the motor command, allowing some errors to be corrected online or avoided.

A goal for the co-acting partner is also developed out of the joint desired state. According to Keller and colleagues (2016), internal models related to a co-acting partner (Other in Figure 1.5) enable the self to predict the actions of partners. Assuming the self has some knowledge of the other's goal (1 in Figure 1.5), the self can enact a top-down simulation that assumes the other's desired state and generates a prediction of the other's motor programs through the other inverse model. For example, if one pianist knows the other pianist's part, predictions can be made about how the other pianist will play that part, especially if the other pianist and their playing style are known to the first pianist. However, it is not necessarily the case that the exact muscle movements are predicted in the other inverse and forward models. Predictions can still be made for movements the self is not entirely familiar with, like a pianist making predictions about the performance of a violinist. The inverse model creates an estimate of what the other's end state will be and is informed by sensory feedback. The predicted other's motor programs are fed into the other forward model to generate a prediction of the other's end state. The estimated state is then compared to the other predicted state generated by the other forward model. Discrepancies between the other estimated and predicted states may be noticed (O2 in Figure 1.5), but there is no way for the self to make adjustments to the other's motor commands. The only possible adjustment would be to the other inverse and forward models so that predictions for future actions would be more accurate. Because of this, the best chamber musicians often rehearse extensively or play in a group with the same members over a long period, allowing the members to learn others' playing styles and thus allowing for better prediction of their actions.

If there is no knowledge of the other's goal (2 in Figure 1.5), the model follows a bottom-up process relying on incoming sensory information to estimate the other's state. This could occur during improvisation, when performing with an unfamiliar partner, or when the partner's part is unknown. In this case, the self still uses the other inverse and forward models to generate an estimation of the motor plan that would bring about the other desired state. If the co-actor is unfamiliar to the self, these estimations may initially be based instead on the self's own action repertoire (Newman-Norlund et al., 2008; Welsh et al., 2013). However, the estimations become more accurate as familiarity with the partner and their action repertoire increases (Loula et al., 2005).When looking at the joint action (i.e., the combined actions of the partners), the model suggests there is an overall joint goal that brings about the joint desired state. The joint goal in the earlier piano example may be to perform a duet piece together with proper pitches and timing throughout. The joint internal model combines the self and other internal models to generate joint estimated and predicted states. The joint estimated and predicted states are compared against the joint desired state. Any discrepancies between the joint estimated and predicted states and the joint desired state can bring about adjustments to the self's performance via the self inverse model. The joint model integrates the self and other internal models and modifies self inverse models to compensate for any discrepancies between the joint output and the joint desired goal.

Another, more minimalist model has been presented – the predictive joint action model (Pesquita, Whitwell, & Enns, 2018). This hierarchical model is composed of three levels: the goal representation level, the action-planning level, and the sensory routing level (see Figure 1.6). The model assumes that partners maintain internal models of themselves and co-acting partners with continuous comparison between an upper level and the level below it. The authors suggest this allows for minimising errors and progression toward the shared goal (Pesquita et al., 2018). The goal representation level characterizes the shared goals, models the desired joint state to the action planning level, and receives an estimation of the joint state from the action planning state. Continuous comparison between these two levels generates the joint state error. Estimates become more accurate with each iteration of the comparison.

The action planning level contains the internal models of the expected action roles for each co-actor in order to achieve the desired joint state. These models can be paired, allowing for different potential combinations of each partner's contribution to the joint action. The internal models at this level use the predicted joint state provided by the goal representation level to generate predictions of the motor states for self and others. These predictions are compared with estimated motor states from the sensory routing level, with discrepancies considered the motor state prediction error.

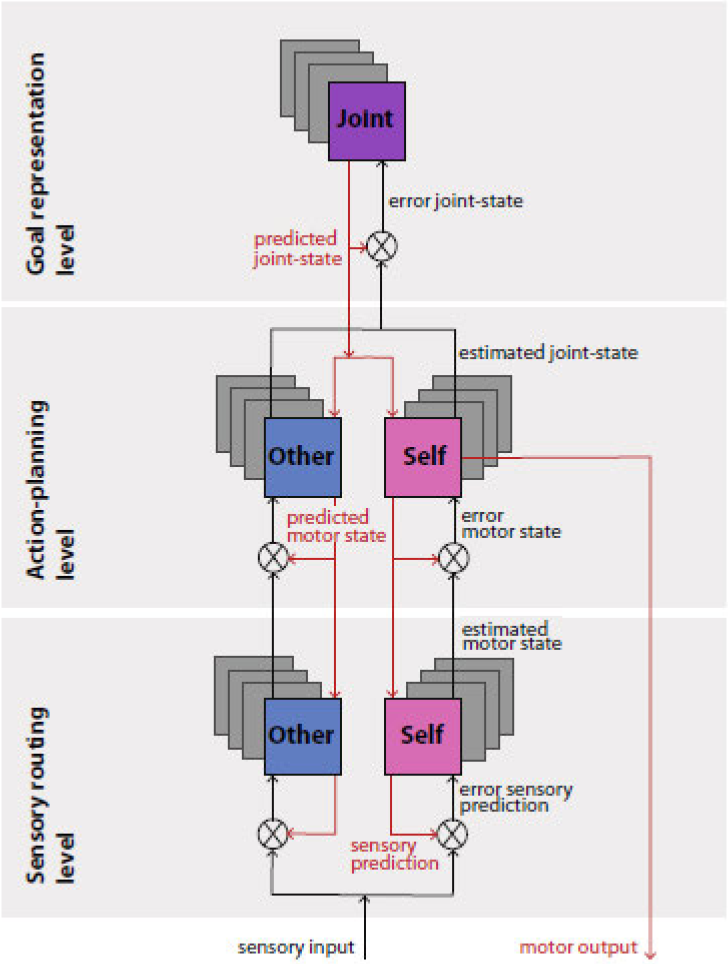


Figure 1.6. The predictive joint-action model is a hierarchical model with three essential levels. From Pesquita, et al. (2018).

The sensory routing level receives sensory input that reflects the outcome of the joint action. The sensory routing level generates sensory predictions for self and other, based on the predicted motor states that are fed in from the action planning level. The sensory predictions are compared with incoming sensory input. Discrepancies between the sensory predictions and input are the sensory prediction error, and the error is used to make adjustments to future predictions.

One main difference between the predictive joint action model and the Keller et al. (2016) model is that the predictive joint action model does not seem to have a comparison between self and other predicted states at the action planning level. According to Keller et al. (2016), as extended from the adaptation and anticipation model of sensorimotor synchronization (Van Der Steen & Keller, 2013), the comparison between self and other predicted states allows for anticipatory error correction. During a performance of a duet, by monitoring the joint performance and each partner's role in that performance, one pianist can adjust their own timing based on the prediction that their originally planned action would not be in synchrony with the expected timing of their partner. The comparison of the two predicted states allows for a compensatory adjustment before the next movement is produced.

1.2.3 Errors Committed During Joint Action

Errors become more complicated when other people are involved. When acting together, the consequences of an error will affect both partners. In this way, the consequences are shared and the error of another can affect performance. Behavioural and neural responses to errors in joint action depend on the context in which they occur. As previously discussed, own errors are often followed by post-error slowing on subsequent trials. However, behavioural adaptation to others' errors depends on the motivation behind the task (de Bruijn, Mars, Bekkering, & Coles, 2012; de Bruijn, Miedl, & Bekkering, 2011). In a competitive go/no-go task in which people responded as fast as possible to specific letters, people sped up in response to errors of their opponent, whereas in the same task with a cooperative goal, people slowed down in response to errors of their partners. This may be due to taking the actions of a partner into account when cooperating, whereas in a competitive situation, the errors of a competitor are actually beneficial. The behavioural response following the error of a competitor suggests that people focussed more on the goal of the task – speed. However, when people were involved in a cooperative situation, behavioural responses to errors were similar regardless of who committed the error (de Bruijn et al., 2012). This suggests that in cooperative situations, the overall shared goal is prioritized over the individual goals. Interestingly, in a flanker task people made more errors after observing an error of a human partner than after observing an error of a computer partner, suggesting that computer actions were not simulated by the partner as were the actions of another human (Núñez Castellar, Notebaert, Van den Bossche, & Fias, 2011). Additional research supports the idea that the actions of non-human partners are not simulated or co-represented at the same level as the actions of human partner (Obhi & Hall, 2011; Sahaï, Desantis, Grynszpan, Pacherie, & Berberian, 2019). Thus, simulation of a partner's actions can affect one's own accuracy, but only when that partner is human.

Perceiving the error of another is different from perceiving a correct response. Evidence looking at the lateralized readiness potential (an ERP component) shows that when a correct response is observed, correct response activation occurs in the observer’s brain; however, following an error, differential motor activation decreases (van Schie, Mars, Coles, & Bekkering, 2004). The lateralized readiness potential showed that the observer’s motor cortex was activated before the actor responded and continued to develop throughout the action. When the actor made an incorrect response, motor activation decreased compared to when a correct response was made. The authors suggested that this pattern of results follows what the observer would have done if doing the task on their own, not maintaining a representation of what the actor is actually doing (van Schie et al., 2004). This is further supported by studies of imitation, in which participants try to replicate the goal of the action instead of imitating the actor (Bekkering, Wohlschlager, & Gattis, 2000), and compensatory ideomotor movements, made by observers when actors are not meeting the action goals (De Maeght & Prinz, 2004; Häberle, Schütz-Bosbach, Laboissière, & Prinz, 2008). These results suggest that when observing an action, people are more likely internally representing that action to its completion instead of representing the error that was committed. The difference in neural activation may be related to internal forward models, with the outcome either matching or not matching the predicted (or internally represented) outcome. As discussed previously, internal forward models can be used to explain differences in neural activity between correct and incorrect responses, suggesting that a mismatch between the predicted and actual outcomes initiates a cascade of neural responses (such as global motor suppression) that are different from neural responses when there is a match between the predicted and actual outcomes. In an observational situation in which the observer is internally representing the action to its completion instead of the error being observed, there would be no need for a global motor suppression because the motor movements are not being controlled by the observer. Self-other distinction plays a role in this, as the awareness that these actions are being performed by another allows the observer to perceive the error while still maintaining the internal representation of the correct predicted outcome. In this way, observers can learn and identify the errors of others, by comparing their predicted outcome with the actual observed outcome.

When looking at EEG studies, self errors elicit an ERN followed by a Pe. As discussed previously in the section on neural indices of error processing, there are scenarios for which there is no internal error information for self errors, such as throwing a dart at a distant target. In such scenarios, the FRN will be elicited as opposed to the ERN. However, the self errors being discussed here are errors that do not rely on external feedback to confirm the error. When a partner makes an error, the ERN and Pe are not elicited (Picton, Saunders, & Jentzsch, 2012), but instead, errors committed by a partner elicit the FRN component. This is in line with the first indicator hypothesis – with self errors, the performer has access to internal self-monitoring information about the error as it is committed, rendering additional feedback of the error redundant. However, that internal error information does not exist for errors that are externally generated, so the external feedback is the only error information available. So whether the error was produced by a co-performer or manipulated feedback, the external feedback is the first indication of the error.

The FRN is often followed by the P300 component. In joint action, errors of a partner elicit a P300 with a larger amplitude than for own errors (Picton et al., 2012). The feedback-related P300 is associated with feedback attentional processing and feedback expectancy (Nieuwenhuis, Yeung, Holroyd, Schurger, & Cohen, 2004). In a piano duet performance study in which pitches were occasionally altered to manipulate auditory feedback, the amplitude of the FRN did not differ whether the manipulated feedback was in the partner's part or in the pianist's own part (Loehr, Kourtis, Vesper, Sebanz, & Knoblich, 2013). Because this study involved manipulated feedback as opposed to errors, the feedback was the first indication of error for both self and other errors. Therefore, when feedback is the only indication of error, there is evidence that self and other errors are processed similarly. However, there is also evidence that manipulated feedback during a piano duet turn-taking task elicits larger FRN and P300 amplitudes for feedback affecting a performer's own part compared to a partner's part (Huberth et al., 2019). When musicians are playing together, they may display post-error slowing for both self and other errors. This makes sense as musicians are attempting to stay synchronous with each other. If one musician makes an error and slows their performance, the other musicians need to slow their performance as well, in order to maintain synchrony.

1.2.4 Investigations into Joint Action using Music

Music is an ideal way to study joint action, as it is a social and cooperative activity in which those involved share a joint goal (D'Ausilio, Novembre, Fadiga, & Keller, 2015). Music-making requires complementary action, not just imitation. Performers share goals, have to adapt to each other, must be familiar with own and others' parts, and are affected by the performance of partners. Additionally, music ensemble performance involves a shared goal that is more important than the individual goal. When playing in an ensemble, musicians need to carefully monitor the performance of others and the progress in terms of the overall goal in addition to monitoring their own performance (Keller et al., 2014; Novembre & Keller, 2014). This monitoring needs to be done in a predictive manner as well, as music performance is an ongoing task (Keller, 2008; Keller et al., 2014). Thus, musicians benefit from knowing, in advance, where their partners are going to be in terms of the music, so that even minor changes in timing can be adapted to immediately. This is similar to how football players must anticipate where their teammates are going to be in order to execute a properly timed and weighted pass (for a review, see Williams, Ford, Eccles, & Ward, 2011), or how a tennis player will predict where their opponent is going to move in order to hit the ball to the opposite side of the court (Triolet, Benguigui, Le Runigo, & Williams, 2013; Williams, Ward, Knowles, & Smeeton, 2002). More generally, this is similar to predicting where another person's hand is going to be when one passes a glass of water or a pen (Controzzi et al., 2018; Kourtis, Sebanz, & Knoblich, 2010).

Research in musical joint action has demonstrated the importance of the mechanisms involved in joint action, including co-representation and simulation (Keller, 2008; Novembre, Ticini, Schütz-Bosbach, & Keller, 2012).

For example, pianists are better able to synchronize with recordings of themselves than with recordings of others (Keller et al., 2007). The authors suggested this is because the sensorimotor system that generated the actions, with its idiosyncratic timing variations, is the same one that carried out the simulation later when synchronising (Keller et al., 2007). Pianists are also better able to synchronize with other pianists who are closely matched in terms of timing in solo performance than those who are not closely matched, and closely matched pairs are more able to mutually adapt to each other's performance (Loehr & Palmer, 2011). Further, motor familiarity with a partner's part increases co-representation as shown through tempo adaptations (Novembre, Ticini, Schütz-Bosbach, & Keller, 2014), ancillary body movements (Ragert et al., 2013), and increased cortical excitability in certain motor neural circuits (Novembre et al., 2012). Thus, familiarity with fellow musicians, their playing style, or their part allows for better prediction of their action outcomes, increasing the ability to coordinate with them.

Due to this extensive training and familiarity with the movements, action-perception coupling in experts is strengthened for actions related to their expertise. This enables experts to quickly identify erroneous actions and adapt their performance if necessary. Musical training provides strong connections between motor movements and auditory outcomes, specifically for the movements and instrument they are trained on (Zatorre, Chen, & Penhune, 2007). This coupling becomes so strong that listening to music performed on their instrument activates involuntary motor activity in expert musicians (Haueisen & Knösche, 2001). Action-perception coupling enables musicians to better simulate and predict the actions of partners. As discussed earlier, this also increases experts' ability to perceive errors in the performance of others.

Musicians are highly skilled in their tasks, having invested thousands of hours of practice (Ericsson, Krampe, & Tesch-Römer, 1993; Sloboda, Davidson, Howe, & Moore, 1996). This allows musicians to simulate musical tasks easily as these tasks are overlearned sensorimotor activities for musicians. Musical expertise increases simulation, as studies have reported increased activation in the lateral dorsal premotor cortex and the pre-supplementary motor area in musicians when listening to music played on their instruments (Bangert et al., 2006; Baumann et al., 2007). Musicians, specifically pianists, use internal simulations in both synchronous (Novembre et al., 2012) and turn-taking performance scenarios (Hadley, Novembre, Keller, & Pickering, 2015). Not only does this expertise increase simulation, it allows for quick error detection, both in own and other's performances (Jentzsch, Mkrtchian, & Kansal, 2014; Maidhof et al., 2009; Panasiti, Pavone, & Aglioti, 2016; Ruiz et al., 2009), and adaptation (Palmer & Drake, 1997).

Taken together, the reviewed literature provides an understanding of what occurs in joint action and how co-representation and simulation facilitate joint action, both generally and, more specifically, in reference to music. In addition, expertise increases one's ability to simulate and predict the actions of others. However, these abilities may be affected when it becomes more difficult to know who is responsible for the outcome, such as when musicians are playing the same music at the same time. In cases like this, the agency of the action becomes unclear, resulting in difficulties in performance monitoring. These issues are discussed in the following section.

1.3 Agency

Agency is the ability to control one's own actions, recognise oneself as the producer of said actions, and use those actions to control events in the environment (Haggard & Chambon, 2012; Haggard & Tsakiris, 2009). There are two distinct aspects of agency – an explicit, reflective understanding that one is the agent of the action and an implicit understanding that one caused the action (for a review, see Haggard & Tsakiris, 2009). The explicit aspect, known as "judgement of agency" is a higher-order, reflective process, whereas the implicit aspect (the "feeling of agency") is a lower-level, sensorimotor process that is immediate (David et al., 2008).

The initial understanding of agency assumed that the feeling of agency emerges from sensorimotor signals that accompany our own actions. This assumption is based on internal forward models, using an efference copy to compare the predicted outcome of a performed action with the actual outcome (Wolpert et al., 1995). Some research suggests that efference copies are not necessary and that a match between intentional state and sensory outcome is sufficient to bring about a feeling of agency (for a review, see Synofzik, Vosgerau, & Newen, 2008). However, there is a growing consensus that the sense of agency arises from multiple cues, including sensorimotor, cognitive, and perceptual (Knoblich & Repp, 2009; Pacherie, 2008, 2012; Sato, 2009; Weiss, Tsakiris, Haggard, & Schütz-Bosbach, 2014). The judgement of agency is a top-down process that relies on inferences, belief states, and intentional states (Wegner, 2003). There is evidence that inferences and belief states alone may be enough to experience judgement of agency (Aarts, Custers, & Wegner, 2005). This can be demonstrated with an example of involuntary or accidental actions. If a person is alone in a room and bumps into a light switch causing a light to come on, the person will readily judge themselves to be the agent of that action, without any intention. The judgement of agency then emerges from the belief of agency and contextual or environmental cues. There was an outcome that required some action and I am the only possible actor, therefore I must have caused the outcome. However, for voluntary actions, an intentional state may be more involved with the judgement of agency. Feeling and judgement of agency may emerge from different processes, but there are two processes that are involved the development of both the feeling and judgement of agency – sensory attenuation and temporal binding.

1.3.1 Sensory Attenuation

Sensory attenuation is the lessening of perceived outcomes when the outcome was self-produced compared to externally-produced (Blakemore, Wolpert, & Frith, 1998). Sensory attenuation is thought to result from a match between the efference copy and the perceived outcome and the researchers suggest that a feeling of agency emerges from this sensory attenuation (Blakemore, Wolpert, & Frith, 2000). Sensory attenuation usually only occurs for self-generated actions not externally-generated actions (Blakemore, Frith, & Wolpert, 1999; Blakemore et al., 2000; Gentsch & Schütz-Bosbach, 2011; Kühn et al., 2011), connecting the reduction in perceived sensory outcomes to the sense of agency. However, one study showed that sensory attenuation occurred both when performing an action and when observing that same action being performed by another (Sato, 2008). There is evidence that belief of agency alone is enough to modulate sensory attenuation (Desantis, Weiss, Schütz-Bosbach, & Waszak, 2012). Further, Weiss et al. (2014) showed that in the neural circuits that controlled the action, corticospinal excitability following an observed action increased as the feeling of agency over the action decreased and vice versa, suggesting that this may be a sensorimotor cue that aids in identifying agency. These studies indicate that belief of agency can be manipulated in cases where action attribution is ambiguous.

1.3.2 Temporal Binding of Actions and Outcomes

A sense of agency relies on a spatio-temporal connection between one's actions and its outcomes (Haggard & Tsakiris, 2009). Because of this, feeling and judgement of agency can be manipulated by delays in timing between the action and the outcome (Tian & Poeppel, 2014; Weiss et al., 2014). An actor has an expectation of the time-course in which they should perceive the outcome, particularly for common actions or expert actions. Temporal delays or interruptions in the action-outcome process indicate that the action has not been carried out properly, that something is not right. For example, if someone turns a light switch on, they expect the light to come on immediately. If it does not, they assume there is something wrong with the light or that they missed the switch. If the light comes on two minutes after they had turned the switch on, they would no longer attribute the light coming on to their own action, but likely assume someone else had turned the switch. This is supported by research that has shown belief of agency decreases as the delay between action and observation of that action increases (Weiss et al., 2014). Further, when people are acting together, performers perceive their own actions earlier in time (i.e., in an anticipatory manner) and actions of others later in time (Capozzi, Becchio, Garbarini, Savazzi, & Pia, 2016), suggesting that this anticipatory temporal binding helps distinguish between one's own actions and the actions of another.

1.3.3 Agency in Ambiguous Contexts

Agency can be ambiguous in joint action if multiple actions are carried out at the same time and have similar predicted effects (Farrer & Frith, 2002). Ambiguity of agency can make cooperative actions more complex because the actors may be unsure of who was responsible for producing what effect, including errors. Reconciling the ambiguity of agency requires the ability to distinguish between self and other (Decety & Sommerville, 2003). Self-other distinction is an important cognitive mechanism involved in joint action and error processing. Activation of the right temporal parietal junction is associated with distinction between self and other (Decety & Grèzes, 2006; Decety & Sommerville, 2003). Without the ability to distinguish between one's own and externally-generated actions, it would be difficult to monitor the progress of actions or determine who was responsible for a particular action. Self-other distinction allows performers to adapt their own performance, if necessary, in order to achieve a shared goal.

However, self-other distinction is not always clear. There is evidence that agency is not processed until a later stage, after the action itself has already been processed, as amplitude of the P300 component increased when an action is considered to be self-generated compared to other-generated (Huberth et al., 2019; Kühn et al., 2011; Loehr et al., 2013). During musical joint action with high levels of agency ambiguity, musicians may not feel the same sense of ownership of the errors committed as they would when agency is not ambiguous. Therefore, when ambiguity of agency is high, people may be less likely to feel ownership of the action or the errors occurring during the action.

In music paradigms, distinction between self and other has been demonstrated through corticospinal excitability and EEG activity. One study used a musical paradigm to show that corticospinal excitability differed depending on whether the action was linked to self or to another during a joint action task (Novembre et al., 2012). Amplitudes of motor-evoked potentials were lower when the action was attributed to self than when attributed to another (see also Schütz-Bosbach, Mancini, Aglioti, & Haggard, 2006). Additionally, there is EEG evidence for a self-other distinction in the processing of auditory feedback (Loehr et al., 2013). Piano feedback was manipulated during ongoing duet performance, eliciting the FRN component for feedback on all altered pitches. The FRN did not differ in amplitude between pitches that were altered in the performer’s own part compared to those altered in the partner’s part. However, the amplitude of the P300 component was significantly larger when the altered pitch was in the performer’s own part compared to the partner’s part. The authors suggested that both parts are monitored, but the self-other distinction is not present until the later stage of processing, as indicated by the difference in P300 amplitude. Interestingly, in a piano duet study that used manipulated feedback in a turn-taking task, self-other distinction was evident in both the FRN and P300 components (Huberth et al., 2019). In that study, manipulated feedback elicited greater FRN and P300 amplitudes when the altered pitch was in the self part compared to the partner’s part. Differences in the results between these studies may be due to the differences in task type (turn-taking versus synchronous).

The attribution of errors is a by-product of performance monitoring in joint action. If a performer knows it was not an own error, then it must have been the partner’s error. For this to occur, one must be able to distinguish between the performance of self and other and have a sense of agency over the action that produced the error. However, as mentioned earlier, the sense of agency decreases with temporal delays and when there is a mismatch between the predicted outcome and the actual outcome (Weiss et al., 2014). Research shows that sense of agency also decreases when an error is made (Knoblich & Sebanz, 2005; Sato & Yasuda, 2005). Further, people are more likely to claim self ownership for actions resulting in successful outcomes and claim other ownership for actions resulting in unsuccessful outcomes (Gentsch, Weiss, Spengler, Synofzik, & Schütz-Bosbach, 2015; Shepperd, Malone, & Sweeny, 2008). These misattributions may be due to the lack of sensory attenuation. When an action outcome is as predicted, sensory output is attenuated and that may cue the actor to attribute that action to the self. When an error occurs, the outcome does not match the prediction, there is no sensory attenuation, and the actor is less likely to attribute that action to the self. Although, for highly trained actions, performers may be more likely to attribute action ownership based on skill level (Repp & Knoblich, 2004). For example, if two pianists are playing together, with one noticeably weaker partner, the weaker partner may be more likely to take ownership of performance failures. Thus, in ambiguous contexts, it could be more likely to attribute an error to a partner than to claim it as a self-made error, but that may depend on the skill level of each partner.

In terms of the model of joint action, ambiguity of agency may lead to the overlapping of self and other internal models. An overlap of internal models would create confusion as to which actor needs to make adjustments to achieve the joint goal. Sensory feedback might then add to the confusion instead of providing useful information that can be used to make adjustments to the motor plans. For example, if two people are moving a couch together and it becomes unbalanced, but neither partner knows why, both may adjust their hold on the couch when only one partner needs to adjust. Instead of steadying the couch, this could cause more instability, leading to the couch falling to the ground.

In summary, agency and self-other distinction are necessary parts of joint action. When agency is ambiguous, there may be an overlapping of self and other internal models, causing performance monitoring to become more complex. Behavioural and neural studies show that agency and self-other distinction are supported by processes including sensory attenuation and temporal binding of actions and outcomes. Self-other distinction is processed at a later stage than the processing of the action itself, as reflected by differences in P300 amplitude for self-generated and other-generated actions. Finally, errors affect self-other distinction through a reduction of sensory attenuation. This may lead performers to misattribute errors to co-performers, especially in contexts where agency is ambiguous.

1.4 Gaps in the Literature

Performance monitoring is a complex cognitive process, involving several different psychological and neurophysiological mechanisms. The research reviewed above provides evidence of the consistent behavioural and neural responses to an error in performance. Behaviourally, errors are generally followed by post-error slowing. Electrophysiological measurements reveal that errors generally elicit an ERN, and this can be observed prior to the error onset in overlearned tasks or in expert performers. The ERN is followed by the Pe, which is associated with error awareness. When another actor is involved in the action, performance monitoring and error processing can become more complex. In such cases, errors committed by the self still elicit the ERN followed by the Pe. However, when the partner makes an error, the FRN is elicited, often followed by the P300.

The current studies aim to bring agency ambiguity into these areas of study to gain a better understanding of how agency affects error processing. Including agency with these areas adds another layer of complexity and there is little understanding as to how agency ambiguity affects behavioural and neural indices of error processing. Investigating the effects of agency ambiguity may reveal an overlap of self and other internal models during joint action and how that can affect estimates of own and other behaviour, specifically when errors are involved. This would allow for an extension of models of joint action to include agency. To this end, this dissertation consists of two studies with expert pianists to investigate effects of agency ambiguity on error processing both during performance and during perception. Music performance is an ideal way to investigate these processes, as it is an ecological task with naturally occurring errors that is inherently social and involves performance monitoring, interpersonal synchronisation, cooperation, and self-other distinction.

1.4.1 Current Studies – Experiment 1

The first experiment aimed to investigate the effect of agency ambiguity in joint action, using a dual piano performance paradigm. In this study, reported in Chapter 2, expert pianists performed memorised piano pieces in pairs. Ambiguity of agency was manipulated by pianists playing either exactly the same notes or playing notes one octave apart, depending on the trial. Both behavioural and neural (EEG) measures were recorded during the experiment. In this way, I was able to explore the effect of agency ambiguity on behavioural and neural responses to errors committed by the self and by the partner, as indicated by post-error slowing and ERP components. This study extends previous studies on error processing in piano performance (Maidhof et al., 2009; Ruiz et al., 2009) to a joint action context. These previous studies found post-error slowing and a pre-ERN that peaked between around 50 ms prior to error onset. The current study was expected to demonstrate post-error slowing following both self and other errors as is in line with previous research on error processing in solo and cooperative tasks. In regards to the EEG data, it was expected that a pre-ERN would be elicited by self errors and followed by a Pe and the FRN component would be elicited by other errors followed by the P300. These predictions are based on the previous research on solo piano error processing research (Maidhof et al., 2009; Ruiz et al., 2009) and errors during cooperative activity (Huberth et al., 2019; Loehr et al., 2013; Picton et al., 2012).

The agency manipulation is a novel contribution. Current models of joint action do not address how agency ambiguity affects internal models. To investigate this, the current study included an agency manipulation to see how agency ambiguity affects performance monitoring and the involvement of agency in joint action models. The agency manipulation was not predicted to affect post-error slowing for self errors, as these errors should have similar error responses and ownership of the errors. For other errors, post-error slowing was predicted to be increased in the high ambiguity condition compared to the low ambiguity condition. The self would have access to additional feedback when making an error (i.e., tactile and proprioceptive feedback, as well as error-related neural activity), but that feedback is not available to the partner. If agency ambiguity does cause an overlap of self and other internal models, there may be an increased sense of ownership or agency in the high ambiguity condition as both players produced the same movements and expected to create the same sound. The overlap of self and other internal models may reduce the effectiveness of sensory feedback information, resulting in confusion as to which partner needs to adjust performance to achieve the joint goal of synchronous playing. The increased sense of agency and reduced effectiveness of sensory feedback may be observed through an increase in post-error slowing when the partner makes an error in the high ambiguity condition.

Expected effects of the agency manipulation on EEG activity were based on previous research both for solo and joint action. By examining the time course of the ERP components, this study may allow for an exploration of how agency affects both self and other internal models, whether it works through the inverse models, forward models, or another process involved in joint action. For both self and other errors, the differences were expected to be observed in the amplitudes of the later positive ERP components (Pe for self errors and P300 for other errors), as agency is generally processed after the error itself is processed. If the self and other internal models overlap during joint action with ambiguous agency, it may result in reduced usefulness of sensory feedback and increased uncertainty about who made the error. This uncertainty may result in changes in amplitude in the later ERP components as detailed below.

For self errors, the pre-ERN was not expected to be affected significantly by the agency manipulation, as previous research has shown that sense of agency is not processed until after the error itself is processed (Kühn et al., 2011; Loehr et al., 2013). The amplitude of the Pe component was predicted to be larger in the low ambiguity condition as an extension of the increased Pe amplitude related to error awareness (Godefroid et al., 2016; Hewig et al., 2011; Murphy et al., 2012; Nieuwenhuis et al., 2001). Errors in the low ambiguity condition may be more salient than those in the high ambiguity condition because sensory feedback may be more useful and thus the error may be more distinctly identified as one's own. This would lead to easier processing of errors and increased ownership of the errors when agency is unambiguous (i.e., in the low ambiguity condition) compared to when agency is ambiguous.

For the partner's errors, the FRN component was not expected to differ significantly by the agency manipulation. The amplitude of the P300 component was predicted to be larger following other errors in the high ambiguity condition compared to the low ambiguity condition, as the shared outcome is more affected by an error in the high ambiguity condition and the sensory feedback may lead to a delay or confusion in error attribution.

Taken together, these results would provide evidence that self and other internal models overlap during joint action when agency is ambiguous, reducing effectiveness of sensory feedback to the internal models. Further, it would suggest that actors prioritise self goals over shared goals in relation to their own performance, but prioritise shared goals over self goals in relation to a partner's performance.

1.4.2 Current Studies – Experiment 2

The second experiment aimed to investigate the effect of belief of agency on neural indices of perception of self and other errors. Results of this experiment should reveal if belief of agency is sufficient to claim ownership of performance, especially errors, and if that ownership affects how the errors are processed. If belief of agency is sufficient to affect error processing, it would suggest that during perception, error processing can be driven by top-down processes. Further, it may be that the belief of agency or even just a feeling of agency (i.e., a non-declarative sense of agency; for a review, see David et al., 2008; Weiss et al., 2014) is aided by the ability to internally simulate the performance accurately. As reported in Chapter 3, pianists who participated in the first experiment returned over a year later for a perceptual study. Participants listened to short excerpts of recordings of performances from the first experiment – their own, their partner's, and those of unfamiliar participants. Behavioural responses and EEG activity were recorded as participants indicated who they thought performed the excerpt and if there was an error in the excerpt. In this way, this experiment investigated the ownership of performance and errors after a considerable delay and the relationship between belief of agency and neural indices of errors.

Behaviourally, participants were predicted to be more accurate at identifying their own performance compared to a partner's or an unfamiliar player's performance. This is based on the research that shows people are better at identifying their own performance and movements compared to that of others (Knoblich & Flach, 2001; Loula et al., 2005; Repp & Knoblich, 2004). Further, pianists are better at synchronizing with their own performances than others' performances (Keller et al., 2007) and better at synchronizing with partners that are matched by preferred performance tempo (Loehr & Palmer, 2011). This suggests that pianists were better able to simulate the performances and form better predictions about the performance through that simulation.

Error excerpts were expected to elicit the FRN followed by the P300 when compared to correct excerpts, although this may depend on if the excerpts were recognised as errors. Because of the differing evidence in the literature on error perception, there were further predictions for the EEG data. Amplitude of the FRN may be greater for self errors compared to partner errors or the errors of an unfamiliar participant regardless of belief of agency (i.e., participant's response). If the self internal model enables an accurate simulation of the performance while the participant is listening, that may trigger sense of ownership regardless of a declarative judgement of agency (i.e., a feeling of agency as opposed to a judgement of agency). This would suggest there is some subconscious ownership of the error facilitated by internal modelling that is specifically tuned to one's own action style (Keller et al., 2007; Keller et al., 2016; Repp & Keller, 2010). Alternatively, there may be no significant difference in FRN or P300 amplitude between self and other, but a difference in amplitude for one or both of these components between self/other and an unfamiliar player. This may suggest that perceptual experience of the previous performance is enough for the pianist to take ownership of the error (Schütz-Bosbach & Prinz, 2007).

1.4.3 Contribution of Current Studies to the Literature

Together, these studies will add to the literature of error processing, joint action, and agency. The current models of joint action do not include agency, nor do they address how agency ambiguity may affect performance monitoring. The current studies are designed to provide a deeper understanding of how people process errors in contexts where agency is ambiguous and may extend joint action models to include agency. Because the studies involve expert participants, these results may generalise to joint actions regularly performed by people in daily life and thus have some expertise in, such as playing team sports, moving heavy objects like furniture, coordinating actions with another to pass something across a longer distance, or coordinating movements with people to avoid bumping into each other on a crowded sidewalk.

Chapter 2

Experiment 1

2.1 Introduction

Performance errors are important, naturally occurring but unexpected events with consistent behavioural and neural responses that manifest across a variety of task domains. Within the context of learning and skill acquisition, errors serve to initiate behavioural adaptation (Ullsperger & von Cramon, 2004). Errors can also be considered within the context of unexpectedness. The adaptive orienting theory of error processing suggests that unexpected events, including action errors, unexpected action outcomes, and unexpected perceptual events, activate an overall suppression network that halts action and affects cognition (Wessel, 2018; Wessel & Aron, 2017). In discrete tasks (e.g., series of trials in reaction time experiments), errors are often followed by slowing (for a review, see Danielmeier & Ullsperger, 2011) and preceded by speeding, reflecting a speed-accuracy trade-off (Wickelgren, 1977). In studies of piano performance (an overlearned, sequential task), errors are both preceded and followed by slower responses in the three keystrokes before and after the error (Maidhof et al., 2009; Ruiz et al., 2009). Additionally, errors in piano performance are associated with a reduction in sound intensity (as indexed by keystroke velocity) on the erroneous keystroke, compared with correct keystrokes (Maidhof et al., 2009; Ruiz et al., 2009). In both discrete and sequential tasks, electroencephalographic (EEG) recordings show a consistent pattern of neural activity associated with an error. A negative deflection called the error-related negativity (ERN) peaks around 50 to 100 milliseconds (ms) after the error (for a review, see Gehring et al., 2012). The ERN is then followed by the error positivity (Pe), peaking between 200 and 500 ms after the error (for a review, see Gehring et al., 2012; Overbeek et al., 2005). In overlearned, sequential tasks, the latency of the ERN shifts, peaking approximately 50 ms before the onset of the error, and thus is sometimes referred to as the pre-ERN (Kalfaoğlu et al., 2018; Maidhof et al., 2009; Ruiz et al., 2009).

Theoretically, the pre-ERN can be accounted for by the first indicator hypothesis of error processing. According to this hypothesis, an error signal is elicited in the brain upon the first indication that an outcome is worse than predicted (Holroyd & Coles, 2002; Stahl, 2010). Thus, an ERN is elicited by the error response and any additional feedback just confirms the error and is redundant. However, if the accuracy of the response can only be known via feedback, then the feedback-related negativity (FRN, which peaks around 250 ms after feedback) would be elicited upon error confirmation. For example, if someone guessed at a true/false question, feedback would be the first indication of an error. This rationale can be applied to motor tasks as well, such as throwing a dart at a distant target. The first indicator hypothesis supposes that the ERN and FRN represent the same cognitive mechanism operating with a different time course and with a different reference (error response for ERN, feedback for FRN). Research using manipulated feedback supports this idea, as self errors elicited the ERN component and manipulated feedback elicited the FRN component (Gentsch, Ullsperger, & Ullsperger, 2009). The authors suggested that these errors activate a common performance monitoring mechanism that is reflected in the two different ERP components. This account can be further applied to overlearned tasks, such as expert pianists playing the piano, in which errors elicit a pre-ERN. Because of their expert knowledge of the feel of the piano and what each key should feel like (i.e., the tactile feedback received from the key when played and the spacing between different keys on the piano), the error response can occur before the full depression of the key. Tactile feedback from finger-key contact (i.e., the point at which the pianist's finger makes first contact with the key) occurs, on average, 69 ms prior to the acoustic onset (Goebl & Palmer, 2008). Thus, with expert pianists, the error may be detected by finger-key contact as opposed to auditory feedback or full key depression.

Errors and adaption to errors become more complex in the context of joint actions, where the task involves more than one person, due to increased potential for errors and possible uncertainty regarding their source. With more than one actor, the consequence of an error can affect just one person, or, more likely, it can affect all the actors involved. One model of joint action based on music ensemble performance posits that joint action is achieved through internal inverse and forward models representing the co-actors (Keller et al., 2016). A joint goal is shared between the co-actors, for example, playing a piano duet with a high part (for self) and a low part (for the partner). The self inverse and forward models are used to generate the motor programs and predict and estimate the consequences of those motor programs of the self. These self models will monitor the self performance – am I playing the correct notes, in the correct order, and at the correct time? Adjustments to self performance are made based on the sensory feedback that is compared to the predictions made by the internal models. The other inverse and forward models represent the co-actor(s) and generate predictions and estimates of their actions. The self will monitor the other's action progression through sensory feedback and make adjustments to the internal models accordingly. For example, maybe the partner is playing faster than the self expected. The self can update its other internal models to reflect this faster pace. The predicted outcomes of self and other actions are compared against the desired goals for the joint action and adjustments can be made online as the action progresses. If one player is playing faster, both can adjust their timing slightly so they start playing in synchrony. Adjustments can be carried out after an error has been made or even before, to prevent an error from occurring. This is possible due to the estimates and predictions generated by the internal models.

As a cooperative group has a shared, common goal, an error will cause a disruption in the progress to achieving the goal. When acting cooperatively in turn-taking tasks, actors slow their responses in reaction both to own errors and to errors of their partner (de Bruijn et al., 2012). Thus, in cooperative turn-taking activities, behavioural responses to errors are similar regardless of who committed the error. This suggests that the overall shared goal is prioritized over individual goals. EEG research into cooperative tasks provides evidence that a partner's error elicits an FRN that peaks approximately 250 ms after feedback, followed by a positive component (P300) peaking between 300 – 400 ms (for a review, see Nieuwenhuis, Holroyd, et al., 2004). A study involving manipulated auditory feedback in piano duos revealed that the FRN was elicited for both own and other actions (Loehr et al., 2013). Additionally, the amplitude of the P300 was larger when the manipulated feedback affected one's own performance and also when it affected the joint outcome compared to when it only affected the other player's performance (Loehr et al., 2013). This suggests that at earlier stages of error processing, own and other's performances are integrated, as reflected by FRN results during a synchronous task.

Self-other distinction may be processed continuously as a task progresses to allow for adjustments during performance. For example, this distinction would allow for compensatory timing mechanisms to keep co-performers in synchrony as each performer would know if they need to slow down or speed up. However, when an error occurs, differentiation between own and other's performances occurs at a later stage of processing, as revealed with the differences in amplitude of the P300 (Keller et al., 2016; Kühn et al., 2011; Loehr et al., 2013). Errors occurring naturally in this context should elicit a pre-ERN for own errors and an FRN for other's errors. We would also expect increased amplitude of the P300, provided the other's error affected joint performance.

With the increased potential for errors that comes along with joint action, there may be ambiguity regarding agency attribution for errors that needs to be resolved. Agency is the ability to control one's own actions, and use those actions to control and effect events in the environment (Haggard & Tsakiris, 2009). Simultaneous actions can create ambiguity of action ownership or agency. If two or more people perform the same action at the same time with the aim of producing the same, single effect, each person may feel ownership of the action and the outcome (Farrer & Frith, 2002). A solo actor relies on the match between predicted sensory effects and actual sensory consequences to acknowledge that their action caused the effect (Sebanz, Bekkering, et al., 2006). When agency is ambiguous, the internal models that represent self and other may start to overlap, resulting in confusion and more difficulty in comparing predictions with the sensory feedback. For example, if two pianists are playing the exact same music at the same time, and one makes a mistake, the auditory feedback may not be enough to determine who made the mistake. The pianists may have to rely on tactile feedback to be certain who made the error.

In performance monitoring tasks that involve manipulated feedback, there is evidence that, when an error is perceived, agency is not processed until a later stage, after the error itself has already been processed (Kühn et al., 2011; Loehr et al., 2013). If agency ambiguity does cause some overlap between self and other internal models, this could result in some confusion or difficulty in error attribution and reduce the usefulness of sensory feedback in informing the actor which internal models need adjusting to correct or compensate for the error. Behaviourally, this may increase post-error slowing for self-committed errors and may elicit post-error slowing for partner-committed errors when agency is ambiguous.

The purpose of the current study was to investigate behavioural and neural responses to naturally occurring errors in a simultaneous, sequential joint action task under conditions where ambiguity of agency is low or high. The specific aim was to test how ambiguity of agency affects adaptation to errors at the levels of behavioural timing and underlying brain processes. This investigation may also reveal how agency fits in to current models of joint action. To this end, pairs of pianists played memorised right-handed piano pieces at different pitches (i.e., low ambiguity condition) and at the same pitch (i.e., high ambiguity condition) as performance and neural (EEG) activity were recorded. Measures of keystroke timing, including interpersonal asynchronies and inter-keystroke intervals (IKIs), and keystroke velocity were analysed to examine pre- and post-error behavioural responses.

Given that the task is a sequential one with naturally occurring errors, post-error slowing and a reduction of keystroke velocity were predicted for self-produced errors, as shown in previous experiments with sequential tasks (Kalfaoğlu & Stafford, 2014; Maidhof et al., 2009; Rabbitt, 1978; Ruiz et al., 2009). Post-error slowing was expected to be similar for both low and high ambiguity conditions for self because these errors should have similar error responses and ownership of the errors. Post-error slowing and reduced velocity were also predicted for other-produced errors, as shown in previous experiments involving errors committed by a partner during cooperative actions (de Bruijn et al., 2012; de Bruijn et al., 2011). For other errors, more post-error slowing was expected in the high ambiguity condition than the low ambiguity condition. There may be some sense of error ownership in the high ambiguity condition as both players produced the same movements and created the same sound. Further, there may be some overlapping of self and other internal models in the high ambiguity condition, leading to confusion in the predicted and estimated states for self and other. This may result in increased post-error slowing in the high ambiguity condition for both self and other errors.

Based on previous literature, we expected to observe the pre-ERN and Pe following self errors and the FRN and P300 following other errors. We expected the amplitude of the pre-ERN would not differ across agency conditions, but the amplitude of the Pe was predicted to be larger in the low ambiguity condition as an extension of the increased amplitude in the Pe related to error awareness. This would suggest increased neural activity in processing errors in which agency was ambiguous. Similarly, we expected a larger P300 amplitude following other errors in the high ambiguity condition as the error would have a greater impact on the joint outcome than in the low ambiguity condition. This pattern of results would provide evidence that in joint action, actors prioritise self goals over joint goals in relation to their own performance, but prioritise joint goals over self goals in relation to a partner's performance. The agency manipulation should allow for an investigation of the role of agency in joint action models. Agency ambiguity may cause an overlap in self and other internal models. This may result in difficulty with self-other distinction and increase the sense of ownership over errors when agency is ambiguous. Amplitudes of the later ERP components (i.e., Pe for self errors and P300 for other errors) may be increased when agency is ambiguous, as more neural processing may be required to distinguish between self and other.

2.2 Methods

2.2.1 Participants

Participants were 48 highly skilled pianists (minimum of 5th Grade in the Australian Music Education Board qualification system or equivalent) with an age range of 18-84 years (*M* = 31.6 years, *SD* = 16.5, 26 female; see Figure 2.1 for age distribution). Forty-one participants self-reported as right handed, five self-reported as left handed, and two self-reported as ambidextrous. All participants had normal hearing and gave informed consent to participate in the study. Participants had an average of 18.8 years of piano playing (*SD* = 15.75, range = 3 – 75 years, median = 13 years). Of those participants who had only a few years of piano playing, piano was not their first or only instrument and they had more training in other instruments. The experiment was approved by the local ethics committee and all participants gave written informed consent for the experiment.

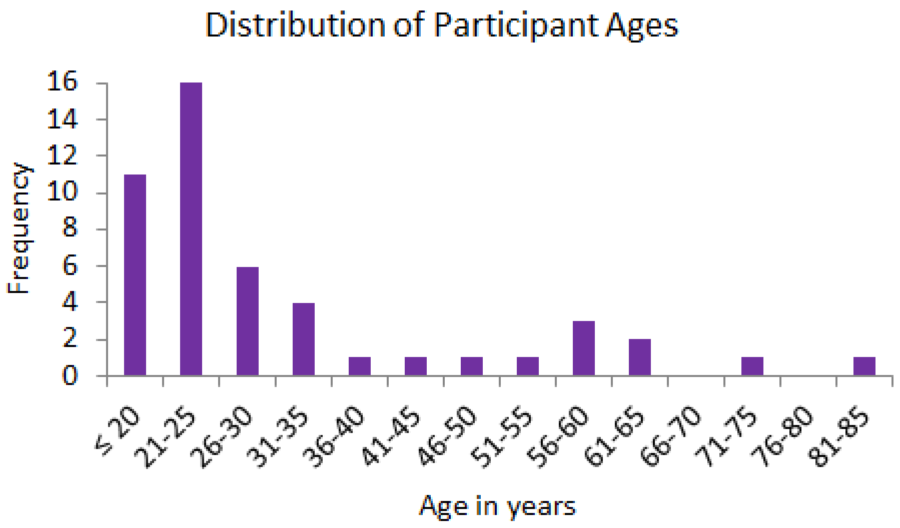
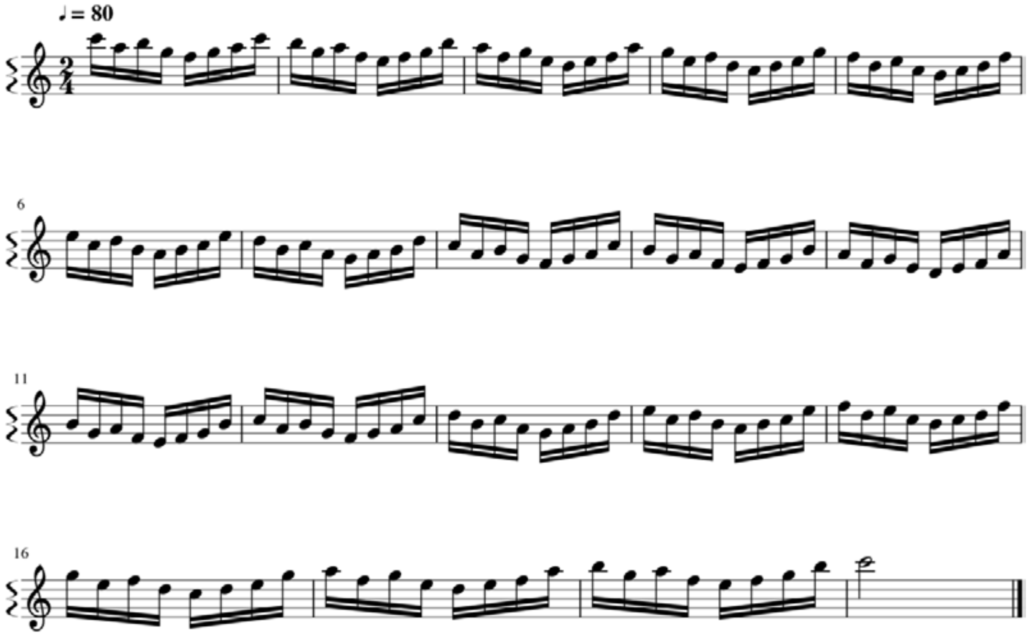


Figure 2.1. Distribution of participant ages. Participants' ages ranged from 18 to 84 years, with the majority of participants under the age of 35 years.

2.2.2 Materials

The piano pieces for the experiment were modified versions of technical piano exercises by Charles-Louis Hanon (Hanon, 1923). There were two sets of six unique pieces, with the second set containing the same six pieces one octave lower than the first set (for an example, see Figure 2.2; the full stimuli can be found in Appendix A). The numbers of notes per piece were 145, 145, 129, 129, 169, and 169. Participants each performed in separate booths on a separate Kurzweil SP2X keyboard set to the "Grand Piano" setting and heard their own and their partner's performances through EEG-compatible insert earphones (Etymotic Research, ER1). The audio was routed through a mixer (Behringer Xenyx 1002) to combine the keyboard outputs before being sent through the earphones to both participants simultaneously in stereo. Custom-built devices converted the MIDI signals from each keyboard into serial signals compatible with Presentation software (Neurobehavioral Systems, Inc.) for each player. A computer program written in Presentation software controlled the visual presentation of stimuli (the scores of the piano pieces) and metronome sounds, logged all MIDI values and onset timings of the keystrokes played by each participant, and sent triggers to the two computers recording the EEG data. Stimuli (in music notation form) were visually presented on 24-inch BENQ monitors. Furthermore, a MOTU micro lite musical instrument digital interface (MIDI) device and a MacBook laptop computer were used to record both participants' performances as separate tracks in a single file (using Reaper v5.04/x64 software). This was used only for measuring key-presses velocity (not timing).

Part B1

Part B2

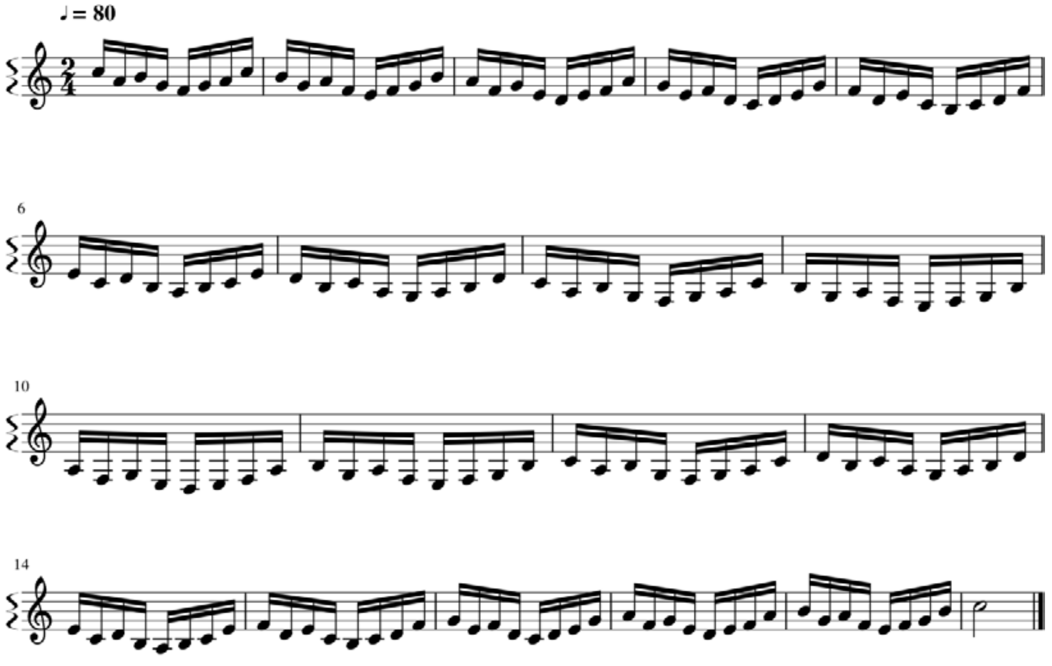



Figure 2.2. Example of stimuli for an unambiguous trial. One pianist plays Part B1 as the other pianist plays Part B2. In an ambiguous trial, both pianists would be playing, for example, B1.

The following self-report questionnaires were employed to measure personality and social factors that have been shown to be related to music performance, inter-personal coordination, or joint action: the Liebowitz Social Anxiety Scale (Baker, Heinrichs, Kim, & Hofmann, 2002; Varlet et al., 2014), the Interpersonal Reactivity Index (Davis, 1980; Novembre et al., 2012), the Big Five Inventory (10-item version; G. Luck, Saarikallio, Burger, Thompson, & Toiviainen, 2010; Rammstedt & John, 2007), the Core Self-Evaluations Scale (Judge, Erez, Bono, & Thoresen, 2003), and the IPC Locus of Control questionnaire (Fairhurst, Janata, & Keller, 2014; Levenson, 1973). These questionnaires made up the first part of the questionnaire for this experiment. The second part of the questionnaire consisted of the Ollen Musical Sophistication Index (Ollen, 2006) and questions related to participants' performance in the experiment, their partner's performance, their music practice habits, how much they prepared for the experiment, and if they were familiar with their partner. The full questionnaire can be found in Appendix B.

2.2.3 Design and Procedure

Each pair of participants played right-handed piano pieces together in two agency conditions in a within-subjects design. In the high ambiguity condition, participants played the exact same piece together. In the low ambiguity condition, participants played the piece one octave apart. As participants played the pieces, keystrokes, MIDI data, and EEG activity were recorded. For each participant, we analysed behavioural and neural responses to own (self) errors and partner's (other's) errors compared to correct keystrokes. IKI was computed during data analysis.

Participants received the piano pieces (scores and recordings) one week before their scheduled experiment session to rehearse and memorise the pieces before the experiment. Participants came in for the experiment in pairs. As they were being prepared with an EEG cap, participants completed the first part of the questionnaire. Once EEG preparation was complete, each participant was brought into an individual EEG booth with their own piano keyboard. Thus, participants could not see or speak to each other throughout the experiment. This was to eliminate any kind of communication between partners during the performance. Musicians often cue each other with verbal communication, eye contact, and body movements to enhance coordination (Bishop & Goebl, 2015; Kawase, 2014; Keller & Appel, 2010); these movements would have affected the EEG recordings. Participants were instructed to focus on synchronicity and keeping in time with their partner (whose performance could be heard via EEG-compatible insert earphones). They were told to continue playing if either they or their partner made an error to make it easier for the duo to regain synchrony after the error. Participants warmed up at their keyboards and then completed several practice trials to become familiar with the procedure and to ensure they had all of the pieces memorised. After the practice trials, participants started the experimental trials. One participant in each pair was responsible for starting each trial by pressing the lowest key on the keyboard. For each trial, each player saw the score of the selected piece for seven seconds on a computer monitor. Then a recorded metronome played four ticks to set the pace for playing. After the fourth metronome tick, participants started playing their respective pieces for that trial. The instructed tempo was 80 beats per minute (bpm), providing for an expected IKI of 188 ms. The duration of the trials ranged from 26 – 34 seconds, depending on piece length.

There were 144 trials split into three blocks of 48 trials. There were 24 possible piano piece combinations given the agency conditions. For example, participants both play the piece in the lower or higher octave (i.e., trials with high agency ambiguity), one participant plays the piece in the lower octave while the other participant plays in the higher octave (i.e., trials with low agency ambiguity), or vice versa. The possible combinations were split into two groups of 12 and each group was randomised twice per block to reduce the chance of a participant consecutively playing the same exact piece. After each block, participants were given a break until both said they were ready to continue. Participants completed the second part of the questionnaire after completing the experimental trials. From start to finish, the experiment took approximately three hours to complete.

2.2.4 Behavioural data analyses

An algorithm was developed in MatLab comparing the MIDI performances with the score templates to locate errors in the performance. To maintain as little variation in timing as possible, only isolated pitch errors were included in the analysis. Thus, to be included, pitch errors had to be preceded and followed by three correct keystrokes (as done in Ruiz et al., 2009), providing sequences of 7 keystrokes for analysis with the error keystroke in the fourth position (keystrokes labelled as follows: E-3, E-2, E-1, E, E+1, E+2, E+3, with E being the error keystroke; see Figure 2.3). Additionally, if keystrokes were more than 75 ms apart from the partner's keystrokes, these were removed from the analysis, as they would no longer be sufficiently synchronous with their partner. The rationale for this criterion was as follows. Preliminary analyses revealed that correct keystrokes were played with an average IKI of 164.14 ms (*SD* = 22.41 ms). One standard deviation less is 141.72 ms and half of that is 70.86 ms. Thus, keystrokes played more than 75 ms apart from a partner's keystroke could be landing between the keystrokes of the partner instead of in synchrony with them. With these restrictions, there was an average of 49.77 errors per participant (*SD* = 64.15) out of an average of 20096.19 keystrokes played (*SD* = 1619.27 keystrokes). The same restrictions and procedure was done for correct keystroke sequences. All correct sequences that met these restrictions were included in the analyses.

To investigate self responses to the errors of a partner, we located 7-note sequences in self playing when the partner made an isolated error. These are referred to as "other" in the analysis, but note that this refers to self responses when the other played an error (or correct). These sequences are labelled the same (E-3 – E+3), but the E in these sequences is the first keystroke the participant played following the error of a partner. IKI and keystroke velocity were analysed in separate 2 x 2 x 7 ANOVAs (Error [error/correct] x Agency [ambiguous/unambiguous] x Keystroke) for both self and other.

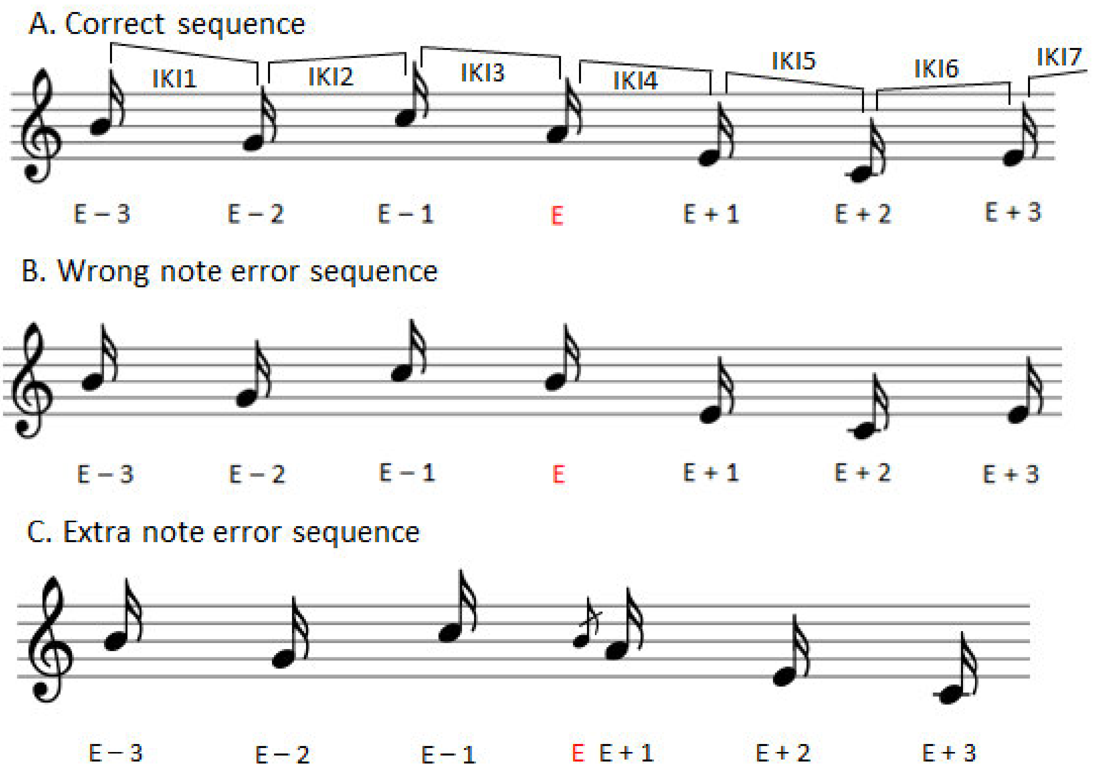


Figure 2.3. Examples of A. Correct note, B. Wrong note error, and C. Extra note error sequences with labels. All sequences are based around the central note labelled E, with the three previous notes labelled E-3, E-2, and E-1 respectively, and the three following notes labelled E+1, E+2, and E+3 respectively. As can be seen, the wrong note is a straight substitution for the correct note, whereas the extra note is played in between two correct notes. Inter-keystroke interval (IKI) placements indicate the location of the IKI for each position.

For each sequence, IKI was measured by subtracting the timing of the first keystroke from the second, the second from the third, and so on. For example, the IKI for keystroke E-3 represents the time in between keystroke E-3 and E-2. If the IKI for E-3 is larger, it means that keystroke E-2 was played late.

Additional analyses were carried out on data split by error type – extra note errors and wrong note errors. Extra note errors occur when a note that is not indicated in the score is inserted in the piece, usually with a very short IKI and low keystroke velocity (Repp, 1996). This can happen quite readily when pianists are playing exercises such as finger fumblers and at a fast pace. Wrong note errors occur when an incorrect note is played instead of a correct note. Data from four participants were excluded from the behavioural analyses because there were less than five errors in at least one condition for each participant (see Table 2.1). Keystroke velocity data were not recorded properly for ten participants due to a technical problem. In addition, several participants were excluded from analyses due to issues with the EEG data (see below). Thus, the IKI analyses were conducted on data from 36 participants and the velocity analyses were conducted on data from 27 participants. More participants were removed from the extra note versus wrong note analysis because there were several participants who made no wrong note errors. These exclusions left 27 participants in the IKI analysis and 22 participants in the velocity analysis (see Table 2.1).

Interpersonal synchronization for each pair was calculated by analysing keystroke asynchronies within the 7-note error and correct sequences. Asynchronies were calculated for error and correct sequences and split by agency ambiguity and error type.

The questionnaire data were collected to examine effects of personality measures on error processing, however there were no correlations found between any of the personality measures and behavioural or neural responses to the errors.

Table 2.1

Distribution of errors by agency and type for each participant

Pair	Participant	Total Isolated Errors	Agency		Error Type	
			Ambiguous	Unambiguous	Wrong Note Errors	Extra Note Errors
1	1	113	57	56	72	41
	2	18	8	10	7	11
2	1	19	6	13	2	17
	2	25	13	12	1	24
3	1	19	8	11	9	10
	2	93	49	44	37	56
4	1	19	14	5	2	17
	2	23	12	11	1	22
5	1	35	13	22	6	29
	2	26	12	14	4	22
6	1	17	5	12	1	16
	2	60	30	30	4	56
7	1	36	15	21	11	25
	2	36	18	18	20	16
8	1	6	3	3	2	4
	2	386	171	215	367	19
9	1	20	10	10	2	18
	2	34	17	17	3	31
10	1	8	4	4	2	6
	2	33	16	17	21	12
11	1	59	23	36	21	38
	2	16	11	5	3	13
12	1	34	19	15	2	32
	2	38	23	15	16	22
13	1	180	96	84	124	56
	2	23	15	8	4	19
14	1	13	5	8	1	12
	2	57	23	34	41	16
15	1	12	5	7	4	8
	2	24	10	14	4	20
16	1	99	50	49	26	73
	2	29	15	14	10	19
17	1	15	5	10	0	15
	2	124	57	67	44	80
18	1	14	9	5	2	12
	2	47	21	26	12	35
19	1	173	88	85	146	27
	2	26	9	17	6	20
20	1	11	3	8	5	6
	2	50	20	30	17	33
21	1	17	6	11	5	12
	2	17	10	7	6	11
22	1	28	16	12	5	23
	2	59	32	27	19	40
23	1	8	4	4	1	7
	2	110	52	58	13	97
24	1	77	40	37	15	62
	2	3	1	2	0	3

2.2.5 EEG data acquisition and analyses

Continuous EEG signals were recorded from 64 Ag/AgCl electrodes placed over the scalp according to the extended 10-20 system (FPZ, FP1, FP2, AFZ, AF3, AF4, AF7, AF8, FZ, F1, F2, F3, F4, F5, F6, F7, F8, FCZ, FC1, FC2, FC3, FC4, FC5, FC6, FT7, FT8, CZ, C1, C2, C3, C4, C5, C6, T7, T8, CPZ, CP1, CP2, CP3, CP4, CP5, CP6, TP7, TP8, PZ, P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, POZ, PO3, PO4, PO7, PO8, OZ, O1, O2, IZ), referenced to linked mastoids (M1, M2). The signals were amplified with a 24-bit BioSemi Active Two system (BioSemi B. V., Amsterdam, Netherlands). Vertical electrooculograms were recorded from the outer canthus of each eye and horizontal electrooculograms were recorded from above and below the right eye for each participant. Data were sampled at 512 Hz. We used FieldTrip MatLab Toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011) for data processing and initial visualisation of the data. A band-pass filter (minimum – 0.5 Hz, maximum – 30 Hz) was applied to the data to remove linear trends, slow drifts, and power line noise. The data were visually inspected and trials containing technical and muscle artefacts (e.g., jaw movement) were removed. The data were cleaned of eye blinks and horizontal eye movements using independent component analysis (ICA). EEG data were epoched from 500 ms before error (or correct) onset to 1000 ms after error (or correct) onset and baseline corrected from 300 ms to 150 ms pre-error onset (as done in Ruiz et al., 2009) for self error/correct sequences and baseline corrected from 200 ms pre-error onset to 0 ms (i.e., at error onset) for other error/correct sequences. For two participants, the EEG activity was only recorded for part of the experiment and thus was not included in the analysis. Data from another two participants were removed due to overly noisy EEG signal and a high level of artefacts throughout the experiment. Data from an additional eight participants were removed due to having less than 15 isolated errors to analyse (in total). With these exclusions, data from a total of 36 participants were included in the overall EEG analysis, 27 participants in the IKI extra/wrong note errors analysis, and 22 participants for the velocity extra/wrong note errors analysis.

Analyses of variance (ANOVAs) were conducted on the mean amplitudes in each condition in specific time windows (see below) for self errors and other errors with electrodes pooled into nine regions of interest (ROIs), split by laterality and anterior/posterior location. Greenhouse-Geisser corrections were applied when the degrees of freedom numerator exceeded one in all analyses. The ROIs were delineated as follows: left anterior – F3, F5, F7, FC3, FC5, FT7; left centre – C3, C5, T7, CP3, CP5, TP7; left posterior – P3, P5, P7, PO3, PO7; middle anterior – F1, Fz, F2, FC1, FCz, FC2; middle centre – C1, Cz, C2, CP1, CPz, CP2; middle posterior – P1, Pz, P2, POz; right anterior – F4, F6, F8, FC4, FC6, FT8; right centre – C4, C6, T8, CP4, CP6, TP8; and right posterior – P4, P6, P8, PO4, PO8 (Sammler, Novembre, Koelsch, & Keller, 2013).

The time windows selected for analyses were 30 to 90 ms for the ERN, 120 to 230 ms for the Pe, and 215 to 300 ms for the FRN. The time windows for the ERN and FRN were selected based on previous research on these components (Gehring et al., 1993; Gehring et al., 2012; Maidhof et al., 2009; Ruiz et al., 2009). As mentioned in the introduction chapter, the Pe is often divided into an early and a late component. For this experiment, the time window of 120 to 230 was selected for the Pe because the data showed an early, frontocentral Pe, but not a later, parietal Pe. Thus, we used a latency that corresponded with research on the early Pe component (Ruchsow et al., 2005; Ullsperger, Fischer, et al., 2014; van Veen & Carter, 2002b).

2.3 Results

2.3.1 Behavioural Results

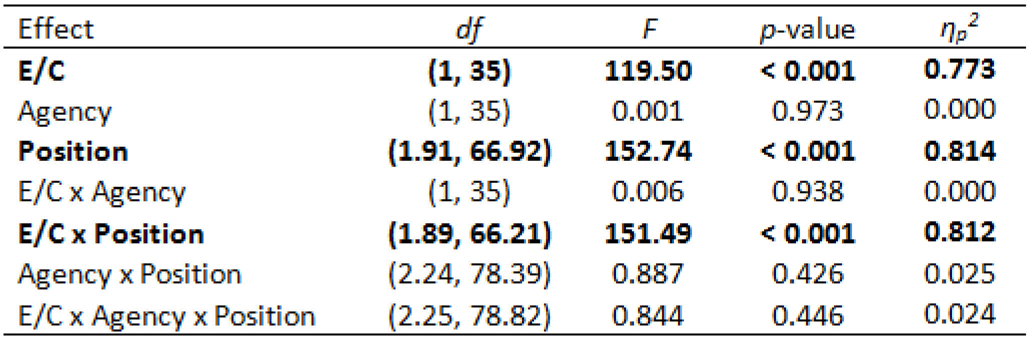
The expected number of keystrokes per participant, if all trials were played perfectly, was 21264. On average, participants played 20096.19 keystrokes (*SD* = 1619.27) and committed 49.77 isolated errors (*SD* = 64.15). The reduced number of keystrokes was observed because participants often missed keystrokes after an error. During some trials, when a mistake was made, participants could not start playing again for a few seconds, or sometimes not until the next trial. This did not occur in any consistent manner (i.e., not for one specific piano piece over or more than any others). Of the isolated errors, an average of 23.94 (*SD* = 30.13) were committed in the high ambiguity condition and 25.83 (*SD* = 34.41) in the low ambiguity condition. There was no significant difference in amount of errors committed in the high ambiguity condition compared to the low ambiguity condition ($t(35) = 1.538$, $p = 0.133$).

2.3.1.1 Inter-Keystroke Interval

Figure 2.4 shows the mean IKI for individual notes during sequences produced by participants (A) or by their partner (B) for both error sequences and correct sequences. The 2 x 2 x 7 (Error/Correct x Agency x Interval Position [IKI1 – IKI7]) ANOVA on self IKI yielded a significant main effect of Error/Correct ($F(1, 35) = 119.5$, $p < 0.001$), a significant main effect of Interval Position ($F(1, 35) = 152.74$, $p < 0.001$), and a significant interaction of Error/Correct and Interval Position ($F(1.89, 66.21) = 151.49$, $p < 0.001$). The full ANOVA results are reported in Table 2.2.

Table 2.2

ANOVA values for behavioural analysis of self IKI with factors of Error/Correct x Agency x Interval Position.



Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 35)**	**119.50**	**< 0.001**	**0.773**
Agency	(1, 35)	0.001	0.973	0.000
Position	**(1.91, 66.92)**	**152.74**	**< 0.001**	**0.814**
E/C x Agency	(1, 35)	0.006	0.938	0.000
E/C x Position	**(1.89, 66.21)**	**151.49**	**< 0.001**	**0.812**
Agency x Position	(2.24, 78.39)	0.887	0.426	0.025
E/C x Agency x Position	(2.25, 78.82)	0.844	0.446	0.024

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct.

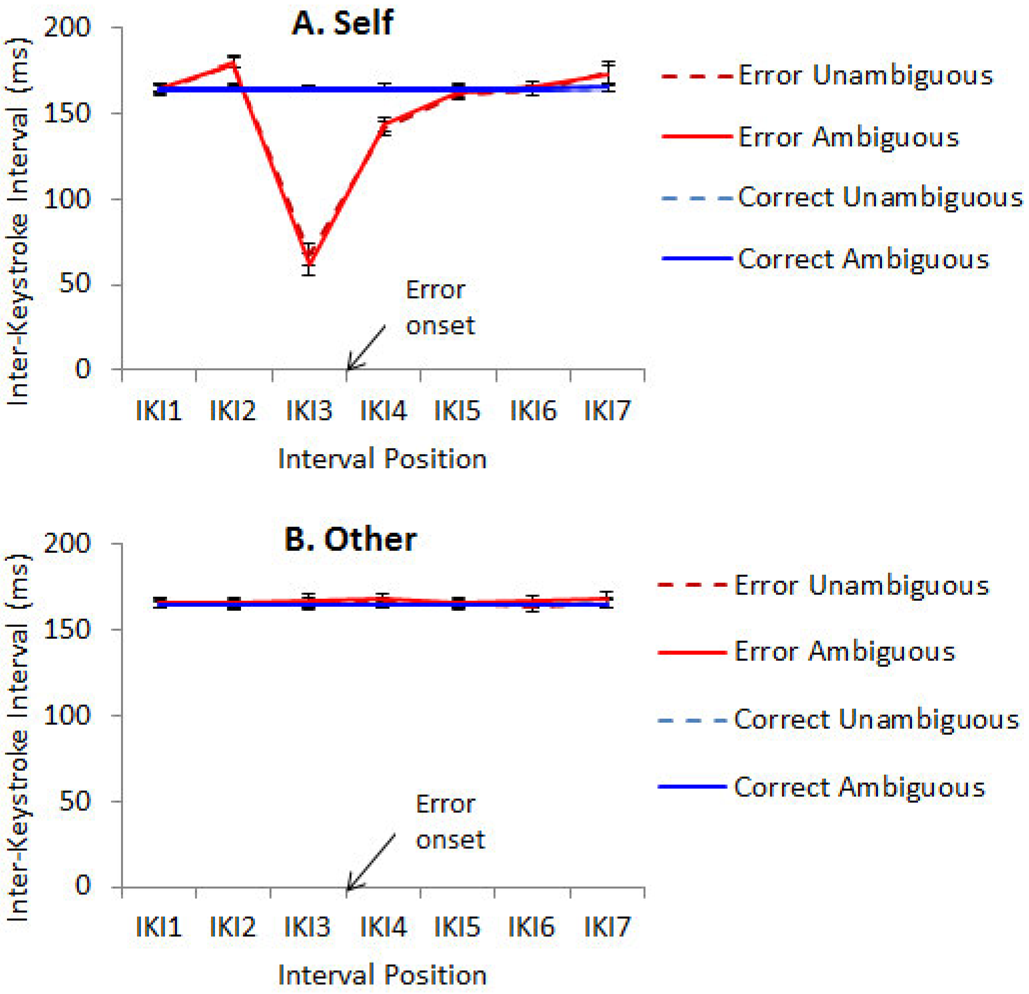
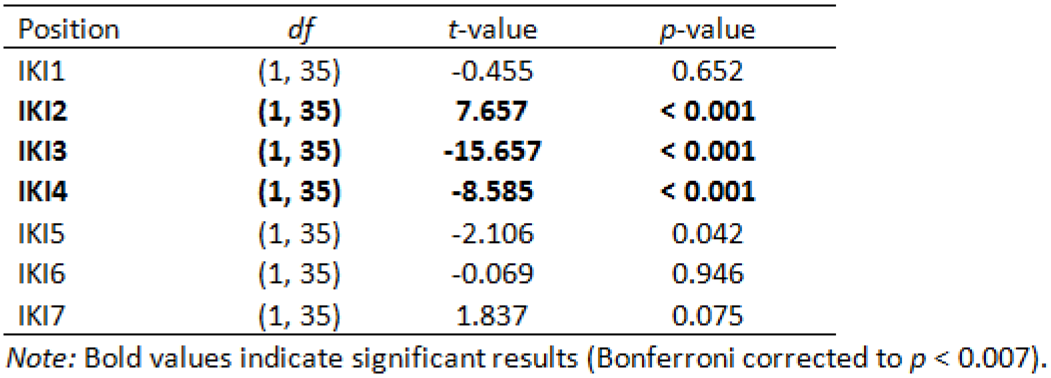


Figure 2.4. Inter-keystroke intervals for error and correct sequences for: A. keystrokes produced by self, and B. keystrokes produced by self when other played error and correct sequences. Onset of the error keystroke is at the tick mark between IKI3 and IKI4. Error bars show standard error.

Follow-up *t*-tests showed that IKI2 was significantly longer during error sequences than during correct sequences and that IKI3 and IKI4 were significantly shorter during error sequences than during correct sequences (see Table 2.3 for statistical values and Figure 2.4A). Although post-error slowing was predicted based on previous studies (for a review, see Danielmeier & Ullsperger, 2011), we observed pre-error slowing, error speeding, and post-error speeding. Participants played keystroke E-1 late, as reflected by the larger IKI2, in the error sequences than the corresponding keystroke in the correct sequences, and keystrokes E and E+1 early in the error sequences than in the corresponding correct keystrokes, as reflected by smaller IKI values at IKI3 and IKI4 (see Figure 2.4A). There were no significant effects or interactions involving agency.

Table 2.3
T-test values for behavioural analysis of IKI between error and correct sequences. Onset of error keystroke is between IKI3 and IKI4.



Position	*df*	*t*-value	*p*-value
IKI1	(1, 35)	-0.455	0.652
IKI2	**(1, 35)**	**7.657**	**< 0.001**
IKI3	**(1, 35)**	**-15.657**	**< 0.001**
IKI4	**(1, 35)**	**-8.585**	**< 0.001**
IKI5	(1, 35)	-2.106	0.042
IKI6	(1, 35)	-0.069	0.946
IKI7	(1, 35)	1.837	0.075

Note: Bold values indicate significant results (Bonferroni corrected to $p < 0.007$).

To further investigate the self-produced pre- and post-error responses, additional analyses were conducted splitting the errors by type – extra note errors and wrong note errors. Figure 2.5 shows the mean IKI for individual notes during sequences produced by participants for extra note error sequences, wrong note error sequences, and correct sequences. A 3 x 2 x 7 ANOVA (Extra/Wrong/Correct x Agency x Interval Position [IKI1 – IKI7]) revealed a significant main effect of Extra/Wrong/Correct ($F(1.41, 36.61) = 70.90$, $p < 0.001$), a significant main effect of Interval Position ($F(1.80, 46.68) = 56.09$, $p < 0.001$), and a significant interaction between Extra/Wrong/Correct and Interval Position ($F(1.90, 49.27) = 62.03$, $p < 0.001$). Full ANOVA results are reported in Table 2.4.

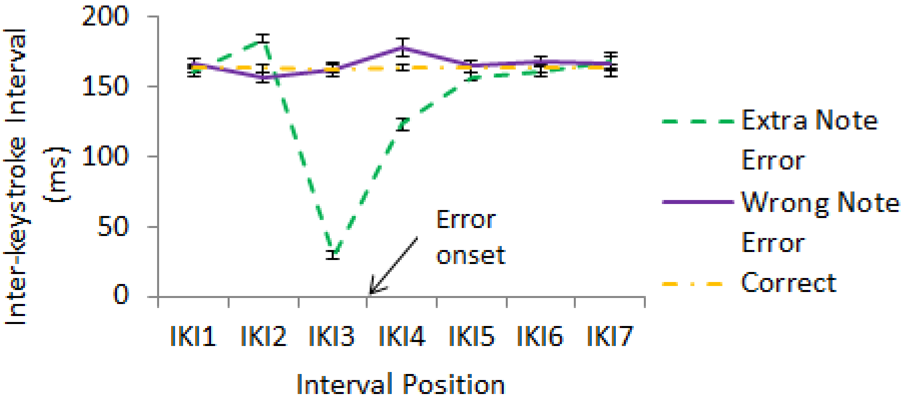


Figure 2.5. Inter-keystroke intervals by error type – extra note error sequences and wrong note error sequences compared to correct sequences. Onset of the error keystroke is at the tick mark between IKI3 and IKI4. Errors bars show standard error.

Table 2.4

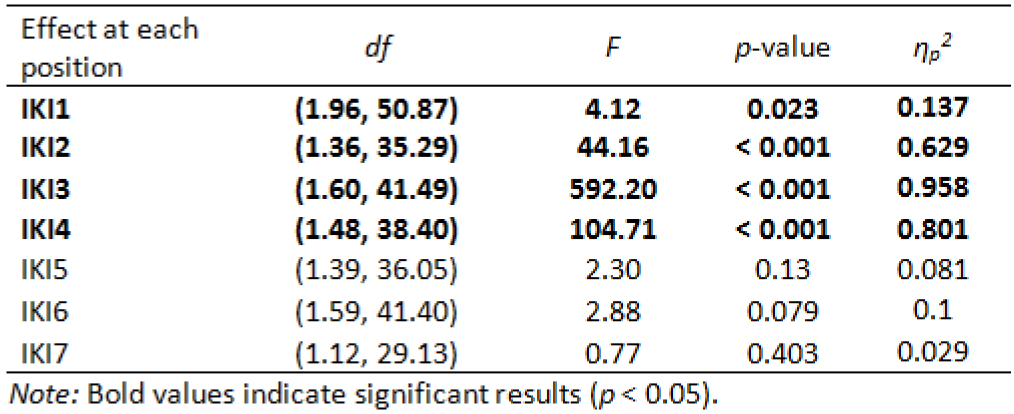
ANOVA values for behavioural analysis of self IKI with factors of Extra Error/Wrong Error/Correct x Agency x Interval Position.

Effect	*df*	*F*	*p*-value	η_p^2
E/W/C	**(1.41, 36.61)**	**70.90**	**< 0.001**	**0.732**
Agency	(1, 35)	1.16	0.291	0.043
Position	**(1.80, 46.68)**	**56.09**	**< 0.001**	**0.683**
E/W/C x Agency	(1.17, 30.50)	3.39	0.07	0.115
E/W/C x Position	**(1.90, 49.27)**	**62.03**	**< 0.001**	**0.705**
Agency x Position	(1.61, 41.79)	1.29	0.282	0.047
E/W/C x Agency x Position	(1.86, 48.32)	1.84	0.171	0.066

Note: Bold values indicate significant results ($p < 0.05$). E/W/C = Extra Error/Wrong Error/Correct.

Follow-up ANOVAs at the Interval Position level revealed a significant difference between Extra, Wrong, and Correct at IKI1 ($F(1.96, 50.87) = 4.12$, $p = 0.02$), IKI2 ($F(1.36, 35.29) = 44.16$, $p < 0.001$), IKI3 ($F(1.60, 41.49) = 592.20$, $p < 0.001$), and IKI4 ($F(1.48, 38.40) = 104.71$, $p > 0.001$). The full ANOVA results are shown in Table 2.5. To identify significant differences between extra note errors, wrong note errors, and correct keystrokes, *t*-tests were carried out on the keystrokes that showed significant main effects in the ANOVAs.

Table 2.5
ANOVA values for behavioural analysis of self IKI at each interval position with factors of Extra Error/Wrong Error/Correct. Onset of error keystroke is between IKI3 and IKI4.



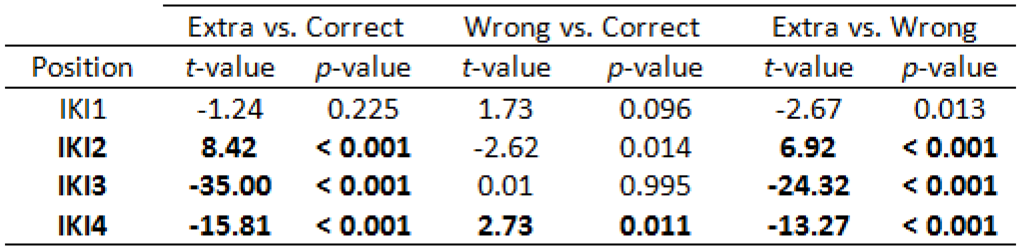
Effect at each position	*df*	*F*	*p*-value	η_p^2
IKI1	**(1.96, 50.87)**	**4.12**	**0.023**	**0.137**
IKI2	**(1.36, 35.29)**	**44.16**	**< 0.001**	**0.629**
IKI3	**(1.60, 41.49)**	**592.20**	**< 0.001**	**0.958**
IKI4	**(1.48, 38.40)**	**104.71**	**< 0.001**	**0.801**
IKI5	(1.39, 36.05)	2.30	0.13	0.081
IKI6	(1.59, 41.40)	2.88	0.079	0.1
IKI7	(1.12, 29.13)	0.77	0.403	0.029

Note: Bold values indicate significant results ($p < 0.05$).

When playing extra note errors compared to playing wrong note errors, participants played keystroke E-1 late, as reflected by a larger value for IKI2, and keystrokes E and E+1 early, as reflected by smaller values for IKI3 and IKI4 (see Table 2.6 for statistical values and Figure 2.5). When compared to correct notes, extra note errors were performed late on keystroke E-1, as reflected by a larger value for IKI2, and early on keystrokes E and E+1, as reflected by smaller values for IKI3 and IKI4 (see Table 2.6 and Figure 2.5). It should be noted that for extra note errors, the error keystroke and the post-error note were played within the timing of a single correct keystroke. The extra note error was performed with an average IKI of 27.61 ms (*SD* = 45.43 ms) and the post-error note was performed with an average IKI of 123.05 ms (*SD* = 41.68 ms). The summed IKIs of E and E+1 in the extra note sequences was, on average, 150.65 ms (*SD* = 33.48 ms), whereas correct keystrokes were performed with an average IKI of 164.14 ms (*SD* = 22.41 ms). Additionally, 93.64 percent of extra note errors were a neighbouring note (i.e., one keystroke up or down) from the pre-error keystroke and 99.11 percent were a neighbouring note from either the pre-error keystroke or the post-error keystroke.

Table 2.6

T-test values for behavioural analysis of IKI between extra note error, wrong note error, and correct sequences for positions where a significant main effect was found. Onset of error keystroke is between IKI3 and IKI4. Degrees of freedom are (1, 26).



	Extra vs. Correct		Wrong vs. Correct		Extra vs. Wrong	
Position	*t*-value	*p*-value	*t*-value	*p*-value	*t*-value	*p*-value
IKI1	-1.24	0.225	1.73	0.096	-2.67	0.013
IKI2	**8.42**	**< 0.001**	-2.62	0.014	**6.92**	**< 0.001**
IKI3	**-35.00**	**< 0.001**	0.01	0.995	**-24.32**	**< 0.001**
IKI4	**-15.81**	**< 0.001**	**2.73**	**0.011**	**-13.27**	**< 0.001**

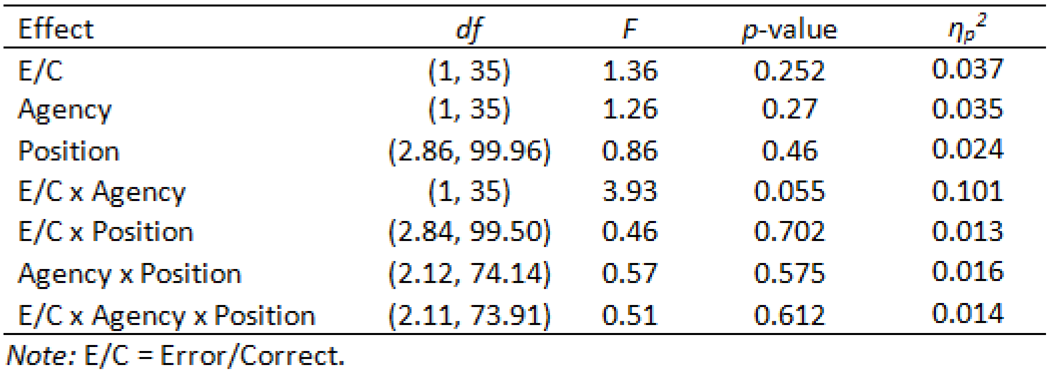
Note: Bold values indicate significant results (Bonferroni corrected to $p < 0.0125$).

When playing wrong note errors compared to correct notes, participants performed keystroke E+1 late, as reflected by a larger value for IKI4 (see Table 2.6 and Figure 2.5). With wrong note errors, post-error slowing was observed, but no pre-error speeding. Extra note errors showed results opposite of the expected pattern – pre-error slowing followed by error speeding and post-error speeding. With the extra note errors, these effects occurred because the extra note subdivided an otherwise accurate timing between keystrokes E-1 and E+1.

The 2 x 2 x 7 (Error/Correct x Agency x Interval Position [IKI1 – IKI7]) ANOVA on other IKI (i.e., IKI of self performance during error and correct sequences by the partner) yielded no significant main effects or interactions (see Figure 2.4B and Table 2.7). Thus, no additional analyses were conducted on these data.

Table 2.7

ANOVA values for behavioural analysis of IKI during performance of error and correct sequences by partner with factors of Error/Correct x Agency x Interval Position.



Effect	*df*	*F*	*p*-value	η_p^2
E/C	(1, 35)	1.36	0.252	0.037
Agency	(1, 35)	1.26	0.27	0.035
Position	(2.86, 99.96)	0.86	0.46	0.024
E/C x Agency	(1, 35)	3.93	0.055	0.101
E/C x Position	(2.84, 99.50)	0.46	0.702	0.013
Agency x Position	(2.12, 74.14)	0.57	0.575	0.016
E/C x Agency x Position	(2.11, 73.91)	0.51	0.612	0.014

Note: E/C = Error/Correct.

2.3.1.2 Velocity

Figure 2.6 shows the mean keystroke velocity for individual notes during sequences produced by participants (A) or by their partner (B) for both error sequences and correct sequences. For each sequence, keystroke velocity was analysed by looking at MIDI velocity. Self keystroke velocity (i.e., keystroke velocity produced by the self during own performance) was analysed with a 2 x 2 x 7 (Error/Correct x Agency x Keystroke) ANOVA on self velocity and showed a main effect of Error/Correct ($F(1, 26) = 98.13$, $p < 0.001$), a significant main effect of Keystroke ($F(2.79, 72.59) = 82.28$, $p < 0.001$), and a significant interaction between Error/Correct and Keystroke ($F(2.81, 72.94) = 79.13$, $p < 0.001$). Full ANOVA results are shown in Table 2.8.

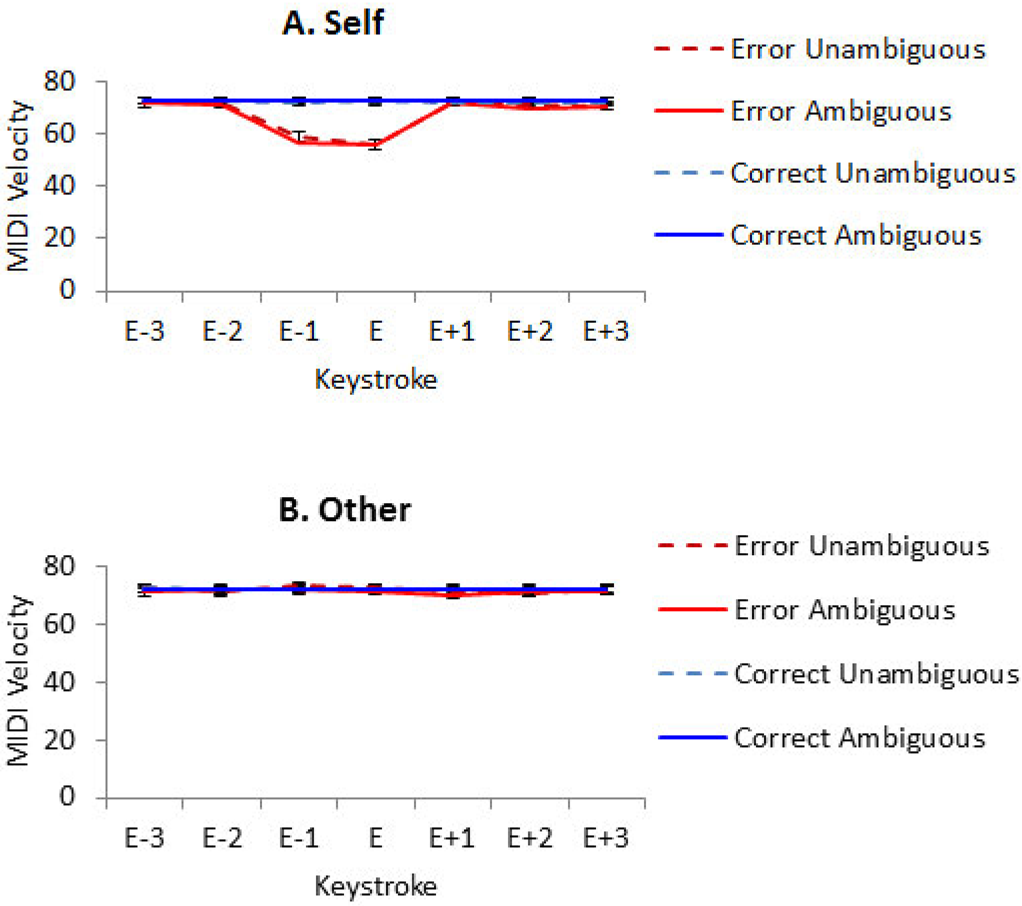


Figure 2.6. Keystroke velocity for error and correct sequences for: A. keystrokes produced by self, and B. keystrokes produced by self when other played error and correct sequences. Error keystroke is labelled E. Error bars show standard error.

Table 2.8

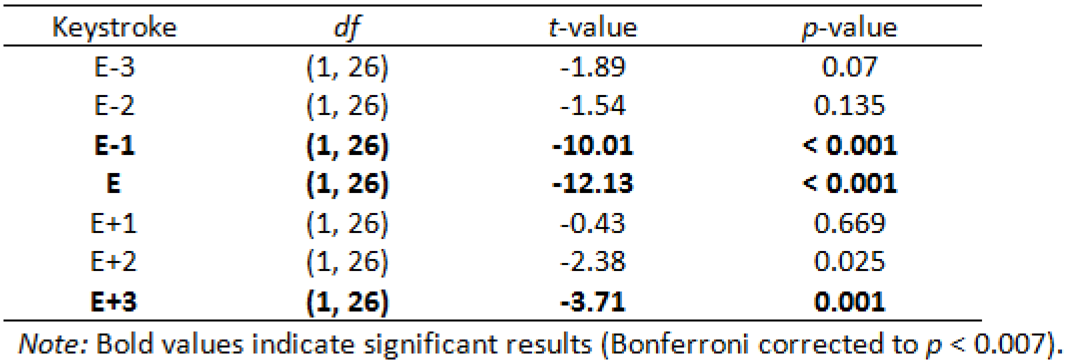
ANOVA values for behavioural analysis of self velocity with factors of Error/Correct x Agency x Keystroke.

Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 26)**	**98.13**	**< 0.001**	**0.791**
Agency	(1, 26)	0.52	0.479	0.019
Keystroke	**(2.79, 72.59)**	**82.28**	**< 0.001**	**0.760**
E/C x Agency	(1, 26)	2.42	0.132	0.085
E/C x Keystroke	**(2.81, 72.94)**	**79.13**	**< 0.001**	**0.753**
Agency x Keystroke	(3.81, 99.11)	1.05	0.384	0.039
E/C x Agency x Keystroke	(3.89, 101.16)	1.07	0.375	0.039

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct.

Follow-up *t*-tests showed a significant difference in velocity between error and correct keystrokes on keystrokes E-1, E, and E+3 (see Table 2.9 for statistical values and Figure 2.6A) As predicted, participants played pre-error keystrokes and error keystrokes with less velocity than correct keystrokes, as shown by smaller velocity values on keystrokes E-1 and E. There were no significant effects or interactions involving agency.

Table 2.9
T-test values for behavioural analysis of self velocity between error and correct keystrokes.



Keystroke	*df*	*t*-value	*p*-value
E-3	(1, 26)	-1.89	0.07
E-2	(1, 26)	-1.54	0.135
E-1	**(1, 26)**	**-10.01**	**< 0.001**
E	**(1, 26)**	**-12.13**	**< 0.001**
E+1	(1, 26)	-0.43	0.669
E+2	(1, 26)	-2.38	0.025
E+3	**(1, 26)**	**-3.71**	**0.001**

Note: Bold values indicate significant results (Bonferroni corrected to $p < 0.007$).

To further investigate the self-produced pre- and post-error responses, additional analyses were conducted splitting the errors by type – extra note errors and wrong note errors. Figure 2.7 shows the mean keystroke velocity for individual notes during sequences produced by participants for extra note error sequences, wrong note error sequences, and correct sequences. A 3 x 2 x 7 ANOVA (Extra/Wrong/Correct x Agency x Keystroke) found a main effect of Extra/Wrong/Correct ($F(1.75, 36.72) = 31.65$, $p < 0.001$), a main effect of Keystroke ($F(3.07, 64.46) = 42.08$, $p < 0.001$), and an interaction between Extra/Wrong/Correct and Keystroke ($F(5.17, 108.62) = 28.97$, $p < 0.001$). Full ANOVA results are shown in Table 2.10.

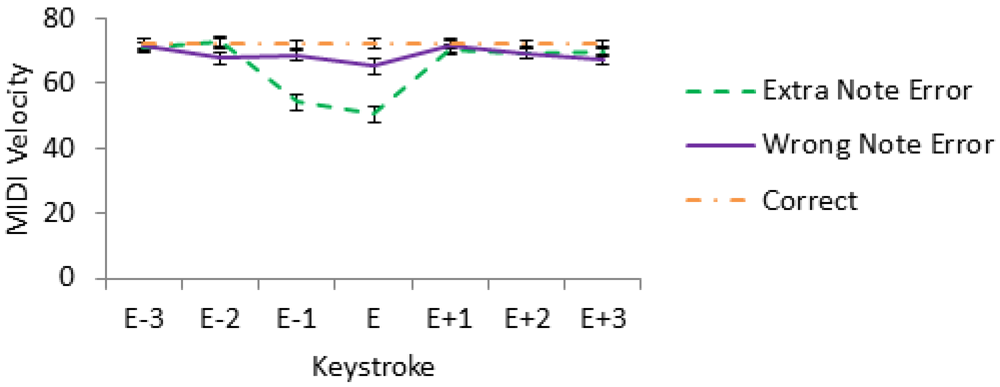


Figure 2.7. Keystroke velocity by error type – extra note error sequences and wrong note error sequences compared to correct sequences. Error keystroke is labelled E. Errors bars show standard error.

Table 2.10

ANOVA values for behavioural analysis of self velocity with factors of Extra Error/Wrong Error/Correct x Agency x Keystroke.

Effect	*df*	*F*	*p*-value	η_p^2
E/W/C	**(1.75, 36.72)**	**31.65**	**< 0.001**	**0.601**
Agency	(1, 21)	0.05	0.821	0.002
Keystroke	**(3.07, 64.46)**	**42.08**	**< 0.001**	**0.667**
E/W/C x Agency	(1.74, 36.59)	0.45	0.615	0.021
E/W/C x Keystroke	**(5.17, 108.62)**	**28.97**	**< 0.001**	**0.580**
Agency x Keystroke	(3.70, 77.70)	0.96	0.428	0.044
E/W/C x Agency x Keystroke	(4.40, 92.41)	0.81	0.532	0.037

Note: Bold values indicate significant results ($p < 0.05$). E/W/C = Extra Error/Wrong Error/Correct.

Follow-up ANOVAs at the Keystroke level revealed a significant difference between Extra, Wrong, and Correct on keystrokes E-2 ($F(1.24, 26.07) = 10.99$, $p = 0.002$), E-1 ($F(1.72, 36.05) = 64.98$, $p < 0.001$), E ($F(1.63, 34.27) = 54.63$, $p < 0.001$), and E+3 ($F(1.27, 26.74) = 12.97$, $p = 0.001$). Full ANOVA results are shown in Table 2.11. When playing extra note errors compared to playing wrong note errors, participants played keystroke E-2 with more velocity and keystrokes E-1 and E with less velocity (see Table 2.12 for statistical values and Figure 2.7). When compared to correct notes, extra note errors were performed with less velocity on keystrokes E-1, E, and E+3. When playing wrong note errors compared to correct notes, participants performed keystrokes E-2, E, and E+3 with less velocity (see Table 2.12 and Figure 2.7).

Table 2.11
ANOVA values for behavioural analysis of self velocity at each keystroke with factors of Extra Error/Wrong Error/Correct.

Effect at each keystroke	*df*	*F*	*p*-value	η_p^2
E-3	(1.61, 33.90)	1.10	0.343	0.05
E-2	**(1.24, 26.07)**	**10.99**	**0.002**	**0.344**
E-1	**(1.72, 36.05)**	**64.98**	**< 0.001**	**0.756**
E	**(1.63, 34.27)**	**54.63**	**< 0.001**	**0.722**
E+1	(1.28, 26.77)	0.72	0.438	0.033
E+2	(1.33, 27.87)	2.38	0.127	0.102
E+3	**(1.27, 26.74)**	**12.97**	**0.001**	**0.382**

Note: Bold values indicate significant results ($p < 0.05$).

Table 2.12
T-test values for behavioural analysis of keystroke velocity between extra note error, wrong note error, and correct keystrokes at keystrokes where a significant main effect was found. Degrees of freedom are (1, 21).

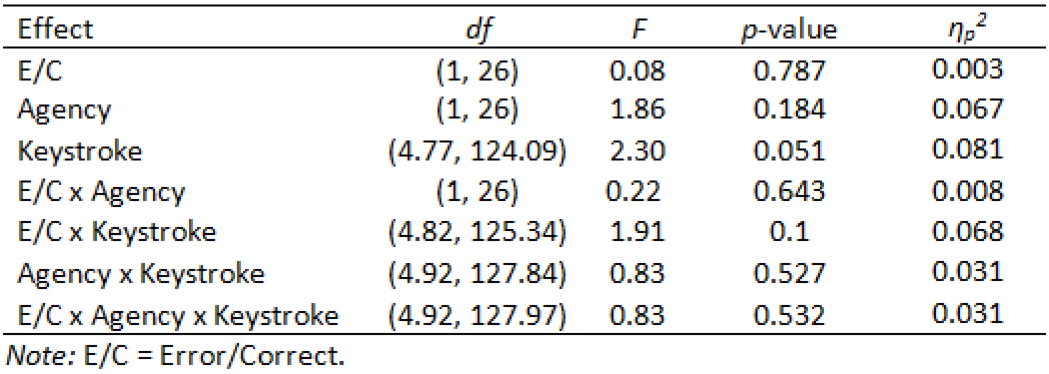
	Extra vs. Correct		Wrong vs. Correct		Extra vs. Wrong	
Keystroke	*t*-value	*p*-value	*t*-value	*p*-value	*t*-value	*p*-value
E-2	1.57	0.13	**-3.01**	**0.007**	**3.81**	**0.001**
E-1	**-10.15**	**< 0.001**	-2.63	0.016	**-7.69**	**< 0.001**
E	**-13.56**	**<0.001**	**-3.40**	**0.003**	**-5.78**	**<0.001**
E+3	**-4.27**	**< 0.001**	**-4.57**	**< 0.001**	2.36	0.028

Note: Bold values indicate significant results (Bonferroni corrected to $p < 0.0125$).

Keystroke velocity during the partner's error and correct sequences (i.e., other velocity) was analysed with a 2 x 2 x 7 ANOVA (Error/Correct x Agency x Keystroke). These analyses yielded no significant main effects or interactions (see Figure 2.6B and Table 2.13), thus no additional analyses were conducted.

Table 2.13

ANOVA values for behavioural analysis of keystroke velocity during performance of error and correct sequences by partner with factors of Error/Correct x Agency x Keystroke.



Effect	*df*	*F*	*p*-value	η_p^2
E/C	(1, 26)	0.08	0.787	0.003
Agency	(1, 26)	1.86	0.184	0.067
Keystroke	(4.77, 124.09)	2.30	0.051	0.081
E/C x Agency	(1, 26)	0.22	0.643	0.008
E/C x Keystroke	(4.82, 125.34)	1.91	0.1	0.068
Agency x Keystroke	(4.92, 127.84)	0.83	0.527	0.031
E/C x Agency x Keystroke	(4.92, 127.97)	0.83	0.532	0.031

Note: E/C = Error/Correct.

2.3.1.3 Asynchrony

Measures of interpersonal asynchrony (i.e., unsigned median, coefficient of variance, and synchronization failure) were calculated for each pair for error and correct sequences in ambiguous and unambiguous agency conditions (see Figure 2.8). Figure 2.8A shows the average unsigned median for synchronization between partners. A 2 x 2 x 7 ANOVA (Error/Correct x Agency x Keystroke) on the average unsigned median revealed a significant main effect of Error/Correct ($F(1, 22) = 343.72$, $p < 0.001$), a significant main effect of Keystroke ($F(1.48, 32.62) = 191.56$, $p < 0.001$), and a significant interaction between Error/Correct and Keystroke ($F(1.51, 33.15) = 195.60$, $p < 0.001$). Full ANOVA results are shown in Table 2.14. Follow-up *t*-tests showed that pairs were more asynchronous when playing error sequences than correct sequences at keystrokes E through E+3 (all *p*-values < 0.001).

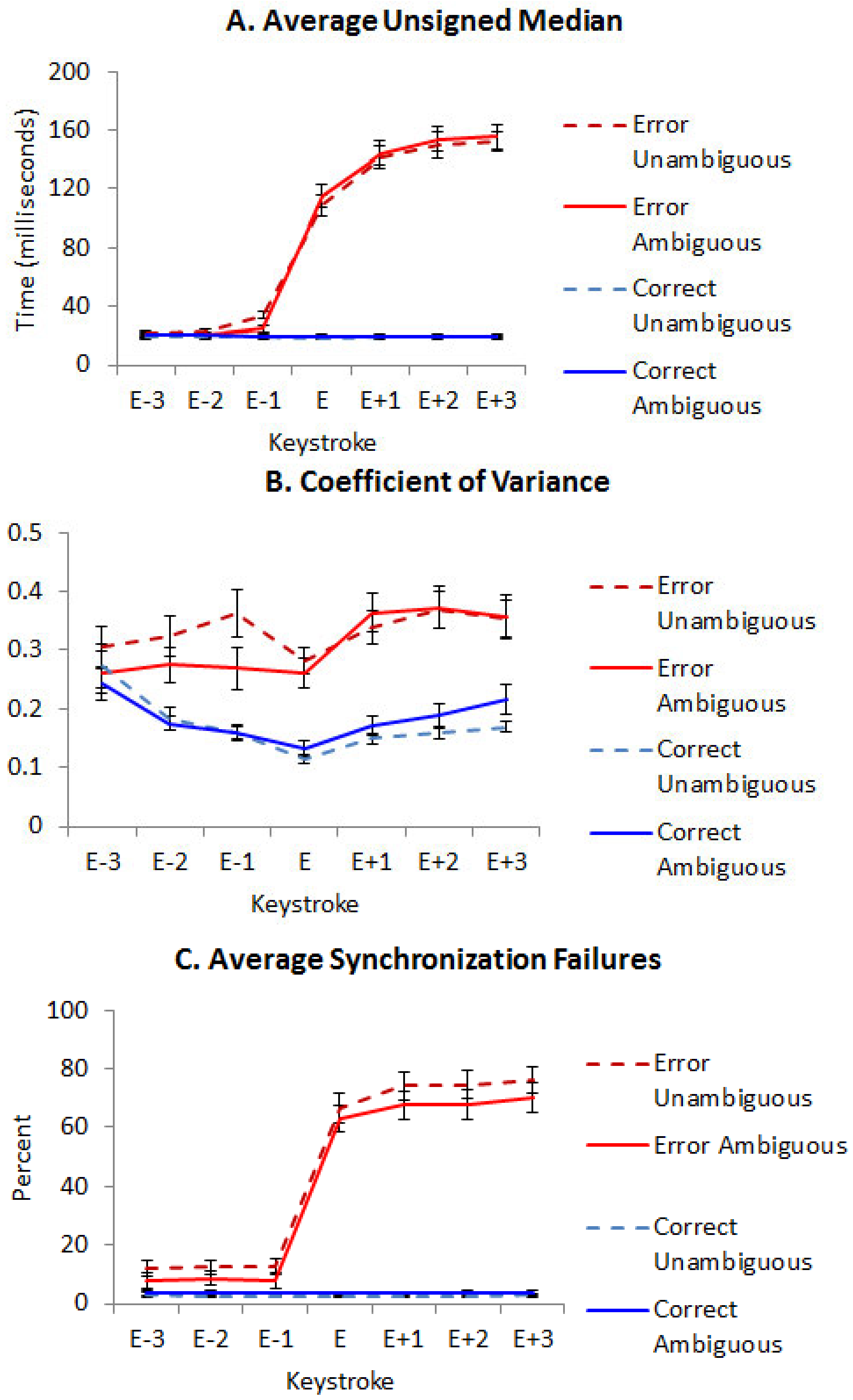
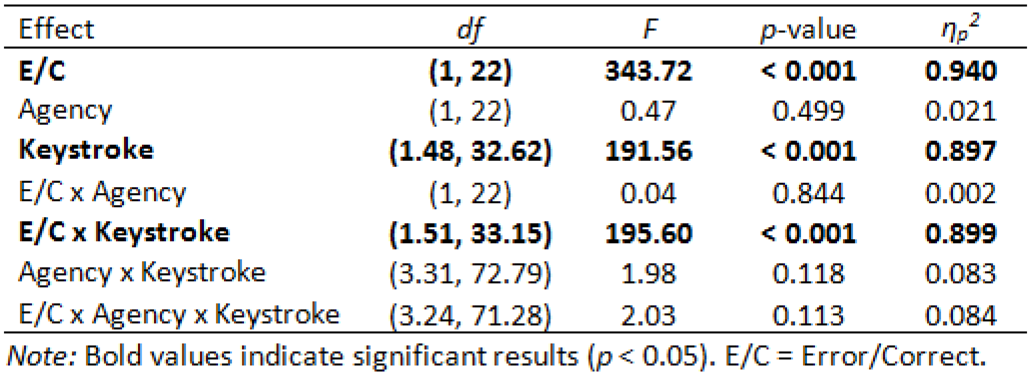


Figure 2.8. Asynchrony data associated with ambiguous and unambiguous agency conditions during error and correct sequences. A. Mean unsigned asynchronies. B. Coefficient of variance. C. Mean synchronization failures. The error keystroke (and respective correct keystroke) is labelled E. Error bars show standard error.

Table 2.14

ANOVA values for behavioural analysis of median unsigned asynchrony at each keystroke with factors of Error/Correct x Agency x Keystroke (n = 23).



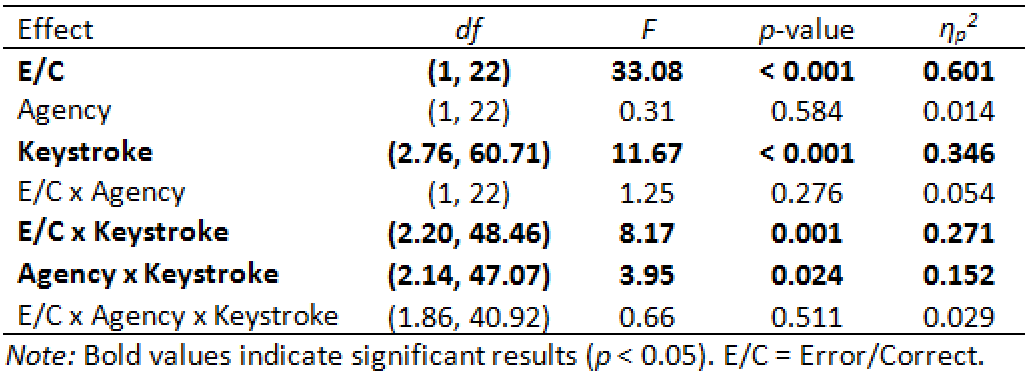
Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 22)**	**343.72**	**< 0.001**	**0.940**
Agency	(1, 22)	0.47	0.499	0.021
Keystroke	**(1.48, 32.62)**	**191.56**	**< 0.001**	**0.897**
E/C x Agency	(1, 22)	0.04	0.844	0.002
E/C x Keystroke	**(1.51, 33.15)**	**195.60**	**< 0.001**	**0.899**
Agency x Keystroke	(3.31, 72.79)	1.98	0.118	0.083
E/C x Agency x Keystroke	(3.24, 71.28)	2.03	0.113	0.084

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct.

Coefficient of variation data (Figure 2.8B) showed higher variability of asynchronies for error sequences than correct sequences already two keystrokes before the error position. The reliability of this result was confirmed in a 2 x 2 x 7 ANOVA (Error/Correct x Agency x Keystroke) showing significant main effects of Error/Correct ($F(1, 22) = 33.08$, $p < 0.001$) and Keystroke ($F(2.76, 60.71) = 11.67$, $p < 0.001$) and significant interactions of Error/Correct x Keystroke ($F(2.20, 48.46) = 8.17$, $p = 0.001$) and Agency x Keystroke ($F(2.14, 47.07) = 3.95$, $p = 0.024$). Full ANOVA results are shown in Table 2.15. Follow-up *t*-tests for the Error/Correct x Keystroke interaction showed there was higher variability of asynchronies when playing error sequences than correct sequences on all except the first keystroke (all *p*-values < 0.001). Follow-up *t*-tests for the Agency x Keystroke interaction showed no significant differences between ambiguous and unambiguous sequences at any keystroke.

Table 2.15

ANOVA values for behavioural analysis of coefficient of variation at each keystroke with factors of Error/Correct x Agency x Keystroke (n = 23).



Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 22)**	**33.08**	**< 0.001**	**0.601**
Agency	(1, 22)	0.31	0.584	0.014
Keystroke	**(2.76, 60.71)**	**11.67**	**< 0.001**	**0.346**
E/C x Agency	(1, 22)	1.25	0.276	0.054
E/C x Keystroke	**(2.20, 48.46)**	**8.17**	**0.001**	**0.271**
Agency x Keystroke	**(2.14, 47.07)**	**3.95**	**0.024**	**0.152**
E/C x Agency x Keystroke	(1.86, 40.92)	0.66	0.511	0.029

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct.

Figure 2.8C shows average synchronization failures. A 2 x 2 x 7 ANOVA (Error/Correct x Agency x Keystroke) on the average synchronization failures revealed a significant main effect of Error/Correct ($F(1, 22) = 309.17$, $p < 0.001$), a significant main effect of Keystroke ($F(1.15, 25.28) = 127.96$, $p < 0.001$), and a significant interaction between Error/Correct and Keystroke ($F(1.15, 25.24) = 126.11$, $p < 0.001$). Full ANOVA results are shown in Table 2.16. Follow-up *t*-tests showed that pairs had greater synchronization failures when playing error sequences than when playing correct sequences at keystrokes E through E+3 (all *p*-values < 0.001). There were no main effects of interactions involving agency.

Table 2.16

ANOVA values for behavioural analysis of synchronization failures at each keystroke with factors of Error/Correct x Agency x Keystroke (n = 23).

Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 22)**	**309.17**	**< 0.001**	**0.934**
Agency	(1, 22)	1.60	0.219	0.068
Keystroke	**(1.15, 25.28)**	**127.96**	**< 0.001**	**0.853**
E/C x Agency	(1, 22)	3.02	0.096	0.121
E/C x Keystroke	**(1.15, 25.24)**	**126.11**	**< 0.001**	**0.851**
Agency x Keystroke	(1.38, 30.43)	0.26	0.689	0.012
E/C x Agency x Keystroke	(1.39, 30.55)	0.30	0.66	0.014

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct.

When split by error type, the asynchrony data show a distinct difference between the error types (see Figure 2.9). Analyses of this data did not include the agency factor because there were too few wrong note errors to split into agency conditions when looking at the data by pairs. It should be noted that the wrong note data were mostly supplied by three pairs for the asynchrony analyses (see Table 2.1). Additionally, the timing for extra note errors was adjusted to reflect the pitch-matched keystrokes. That is, since the extra note errors were very quick notes inserted into an otherwise correct sequence, the asynchrony calculations were adjusted so that the extra note was treated as an extra note. The differences in timing between partners was calculated as usual for the first three keystrokes, but skipped the extra note error to calculate asynchrony with the three post-error keystrokes, as those were more closely matched in time and matched in pitch between the partners. Thus, these sequences show six keystrokes instead of the previous sequences that showed seven keystrokes.

A 3 x 6 ANOVA (Extra/Wrong/Correct x Keystroke) of the median unsigned asynchrony values revealed a significant main effect of

Extra/Wrong/Correct ($F(1.08, 21.30) = 25.69$, $p < 0.001$), a significant main effect of Keystroke ($F(3.53, 74.13) = 3.74$, $p = 0.011$), and a significant interaction between Extra/Wrong/Correct and Keystroke ($F(4.40, 92.30) = 3.95$, $p = 0.004$). Follow-up ANOVAs at the Keystroke level revealed a significant difference between extra note errors, wrong note errors, and correct keystrokes at every keystroke location (see Table 2.17 for full results).

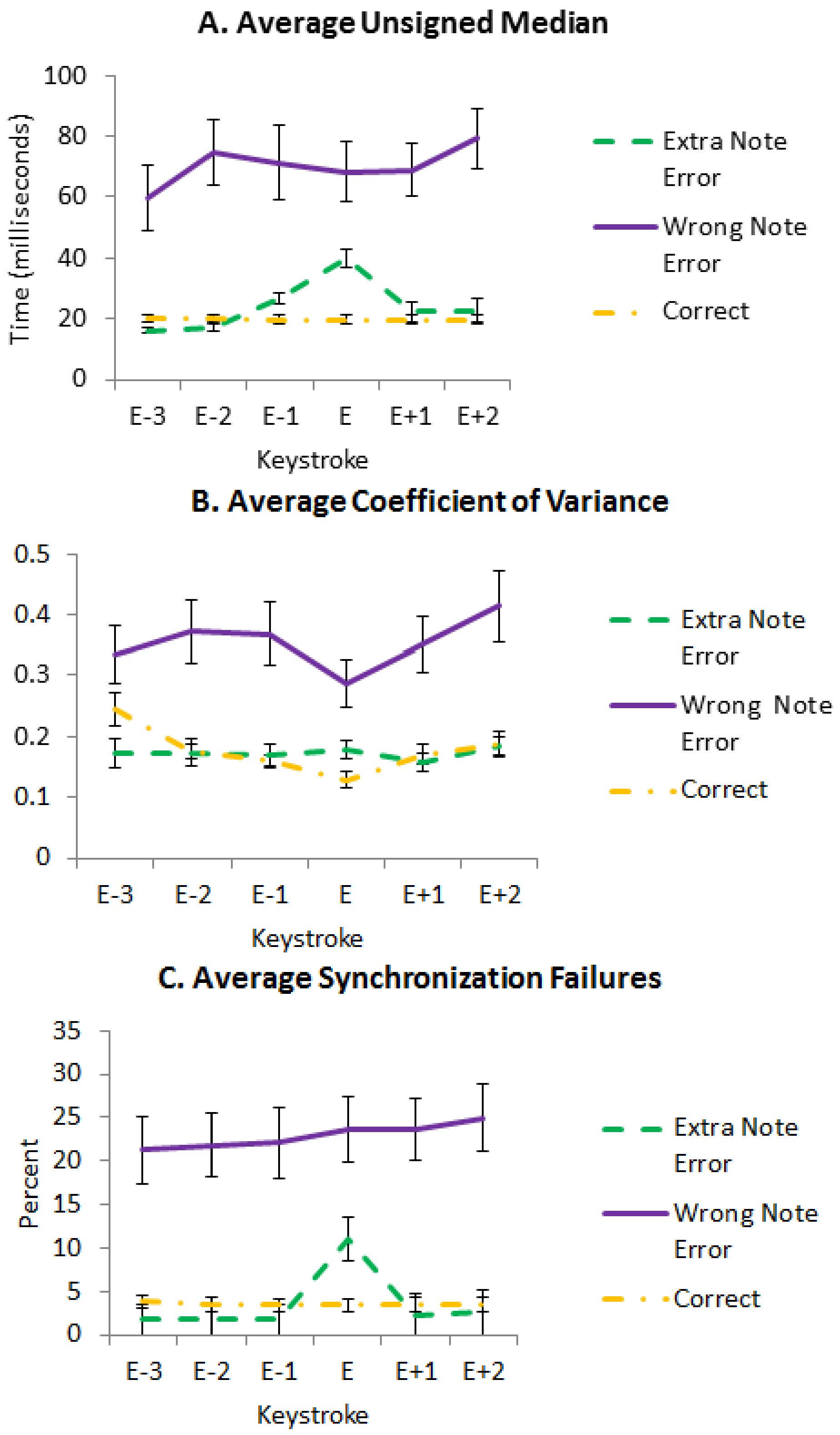
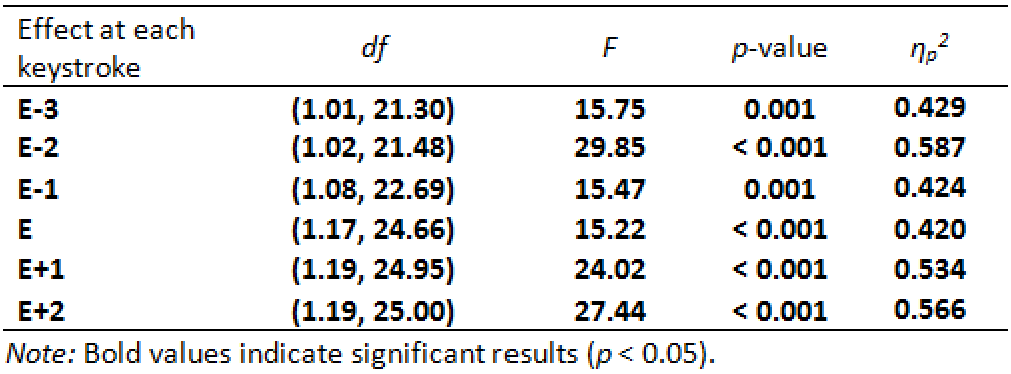


Figure 2.9. Asynchrony data associated with extra note errors and wrong note errors during error and correct sequences. A. Mean unsigned asynchronies. B. Coefficient of variance. C. Mean synchronization failures. For wrong note and correct sequences, the error keystroke (and respective correct keystroke) is labelled E. For extra note error sequences, E represents the post-error note. Error bars show standard error.

Table 2.17

ANOVA values for behavioural analysis of median unsigned asynchrony at each keystroke with factors of Extra Error/Wrong Error/Correct.



Effect at each keystroke	*df*	*F*	*p*-value	η_p^2
E-3	**(1.01, 21.30)**	**15.75**	**0.001**	**0.429**
E-2	**(1.02, 21.48)**	**29.85**	**< 0.001**	**0.587**
E-1	**(1.08, 22.69)**	**15.47**	**0.001**	**0.424**
E	**(1.17, 24.66)**	**15.22**	**< 0.001**	**0.420**
E+1	**(1.19, 24.95)**	**24.02**	**< 0.001**	**0.534**
E+2	**(1.19, 25.00)**	**27.44**	**< 0.001**	**0.566**

Note: Bold values indicate significant results ($p < 0.05$).

Finally, follow-up *t*-tests showed that the median unsigned asynchrony was significantly lower at keystroke E-3 during extra note error sequences than during correct sequences and significantly higher at keystroke E (the post-error keystroke in the extra note sequences) in the extra note error sequences than the correct sequences (see Table 2.18). Pairs were more synchronous at the beginning of extra note error sequences than correct sequences, but less synchronous on the keystroke following an extra note error compared to a correct keystroke. When comparing wrong note error sequences to correct sequences, median unsigned asynchrony was significantly higher for all keystrokes during wrong note errors sequences. Pairs played wrong note error sequences with consistently less synchrony than correct sequences. When comparing extra note error sequences to wrong note error sequences, median unsigned asynchrony was significantly higher during wrong note error sequences for all keystrokes except the error keystroke in the wrong note error sequences and the post-error keystroke in extra note error sequences. Pairs played wrong note error sequences with less synchrony than extra note error sequences except when playing the error itself.

Table 2.18

T-test values for behavioural analysis of median unsigned asynchrony between extra note error, wrong note error, and correct keystrokes at keystrokes. Degrees of freedom are (1, 21).

	Extra vs. Correct		Wrong vs. Correct		Extra vs. Wrong	
Keystroke	*t*-value	*p*-value	*t*-value	*p*-value	*t*-value	*p*-value
E-3	**-4.17**	**< 0.001**	**3.80**	**0.001**	**-4.12**	**< 0.001**
E-2	-2.88	0.009	**5.33**	**< 0.001**	**-5.62**	**< 0.001**
E-1	2.36	0.028	**4.27**	**< 0.001**	**-3.65**	**0.001**
E	**5.13**	**< 0.001**	**5.04**	**< 0.001**	-2.52	0.02
E+1	0.66	0.518	**5.82**	**< 0.001**	**-4.55**	**< 0.001**
E+2	0.58	0.566	**6.24**	**< 0.001**	**-4.87**	**< 0.001**

Note: Bold values indicate significant results (Bonferroni corrected to $p < 0.00278$).

2.3.2 EEG Results

2.3.2.1 Error-related Negativity

Based on previous research of solo piano performance (Maidhof et al., 2009; Ruiz et al., 2009), it was predicted that self-produced errors would elicit a pre-ERN. However instead of the pre-ERN, self-produced errors elicited an ERN with a latency of 30 to 90 ms after self error onset (see Figure 2.10).

A 2 x 2 x 3 x 3 (Error/Correct x Agency x Lateralisation [left/middle/right] x Anterior/Posterior [anterior/centre/posterior]) ANOVA on data in this time window yielded an interaction of Error/Correct and Anterior/Posterior ($F(1.12, 39.21) = 6.55$, $p = 0.012$) and a 3-way interaction between Agency, Lateralisation, and Anterior/Posterior ($F(3.08, 107.95) = 2.71$, $p = 0.047$). No other main effects or interactions were significant. Full ANOVA results are shown in Table 2.19.

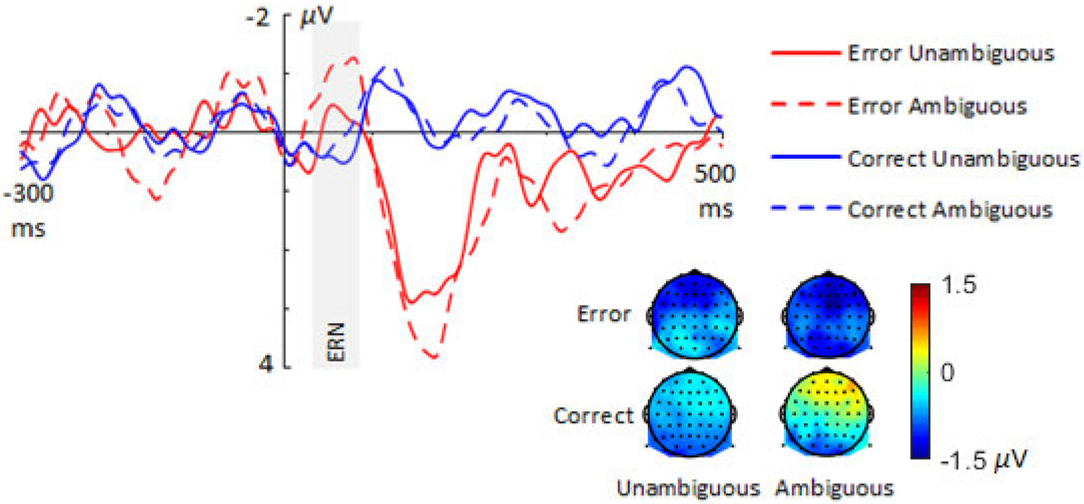


Figure 2.10. Upper – Grand-averaged waveforms showing the ERN (30 – 90 ms, shaded) during self performance time-locked to onset of correct (blue) and error (red) keystrokes at electrode FCz. The solid lines represent playing in the unambiguous condition, dashed lines represent playing in the ambiguous condition. Lower – Scalp voltage distributions for each condition at 60 ms.

Table 2.19

ANOVA values for analysis of ERN during performance of error and correct keystrokes at a time window of 30 – 90 ms with factors of Error/Correct x Agency x Lateralization x Anterior/Posterior.

Effect	*df*	*F*	*p*-value	η_p^2
E/C	(1, 35)	0.68	0.414	0.019
Agency	(1, 35)	2.18	0.149	0.059
L/R	(1.98, 69.28)	1.72	0.186	0.047
A/P	(1.18, 41.43)	2.89	0.091	0.076
E/C x Agency	(1, 35)	0.30	0.589	0.008
E/C x L/R	(1.53, 53.56)	0.40	0.617	0.011
Agency x L/R	(1.66, 57.98)	0.43	0.615	0.012
E/C x Agency x L/R	(1.82, 63.78)	0.60	0.538	0.017
E/C x A/P	**(1.12, 39.21)**	**6.55**	**0.012**	**0.158**
Agency x A/P	(1.11, 38.97)	0.45	0.529	0.013
E/C x Agency x A/P	(1.89, 38.11)	0.46	0.517	0.013
L/R x A/P	(2.86, 99.93)	1.12	0.344	0.031
E/C x L/R x A/P	(2.48, 86.94)	1.98	0.134	0.053
Agency x L/R x A/P	**(3.08, 107.95)**	**2.71**	**0.047**	**0.072**
E/C x Agency x L/R x A/P	(3.26, 114.05)	1.99	0.114	0.054

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct; L/R = Left/Middle/Right; A/P = Anterior/Centre/Posterior.

After breaking the ANOVA down by Anterior/Posterior (anterior/centre/posterior), a main effect of Error/Correct was found in the Anterior ($F(1, 35) = 5.20$, $p = 0.029$) region of interest (see Figure 2.11). There were no other main effects or interactions. Full ANOVA results are shown in Table 2.20. The amplitude of the ERN when playing an error was significantly larger than when playing a correct keystroke in anterior regions of interest, regardless of Agency or Lateralisation ($t(35) = 2.28$, $p = 0.029$; see Figure 2.11).

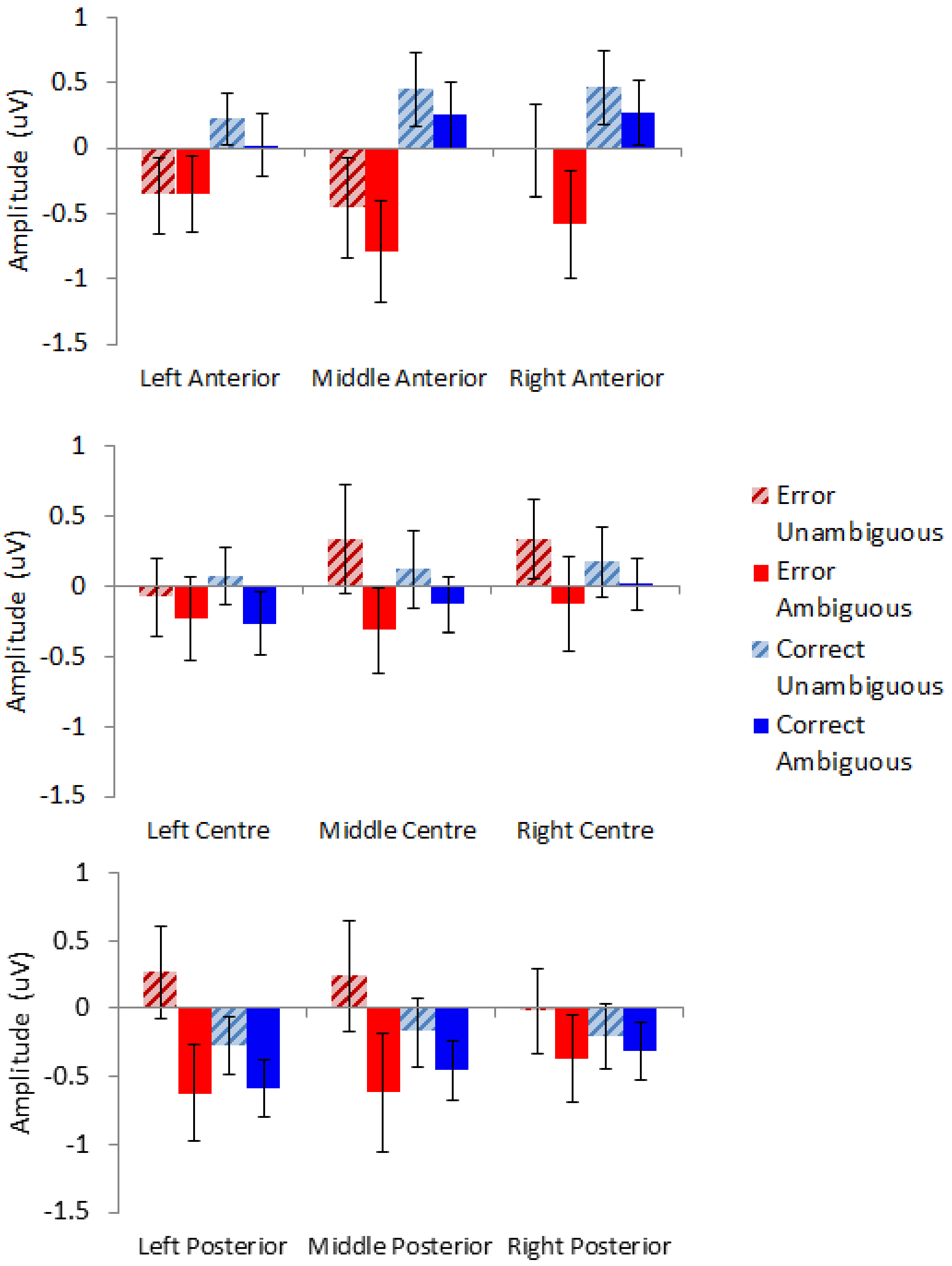


Figure 2.11. Amplitude (in microvolts) of ERN for regions of interest time-locked to error and correct keystrokes in ambiguous and unambiguous conditions of agency.

Table 2.20

ANOVA values for analysis of ERN during performance of error and correct keystrokes at a time window of 30 – 90 ms with factors of Error/Correct x Agency x Lateralization for Anterior regions of interest.

Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 35)**	**5.20**	**0.029**	**0.129**
Agency	(1, 35)	0.72	0.402	0.02
L/R	(1.97, 68.86)	2.47	0.093	0.066
E/C x Agency	(1, 35)	0.04	0.84	0.001
E/C x L/R	(1.58, 55.33)	1.89	0.169	0.051
Agency x L/R	(1.61, 56.28)	1.22	0.295	0.034
E/C x Agency x L/R	(1.78, 62.31)	1.44	0.246	0.039

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct; L/R = Left/Middle/Right.

2.3.2.2 Error Positivity

Based on previous research in error processing (Gehring et al., 2012; Overbeek et al., 2005), a Pe was predicted to follow the ERN in the self EEG data. In the current study, a Pe was observed in the time window of 120 – 230 ms (see Figure 2.12).

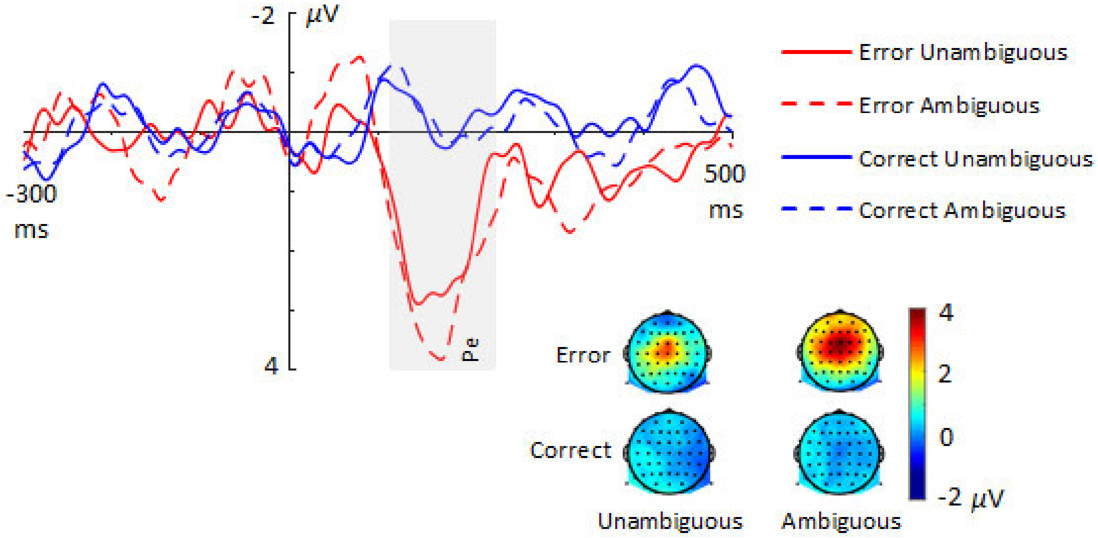
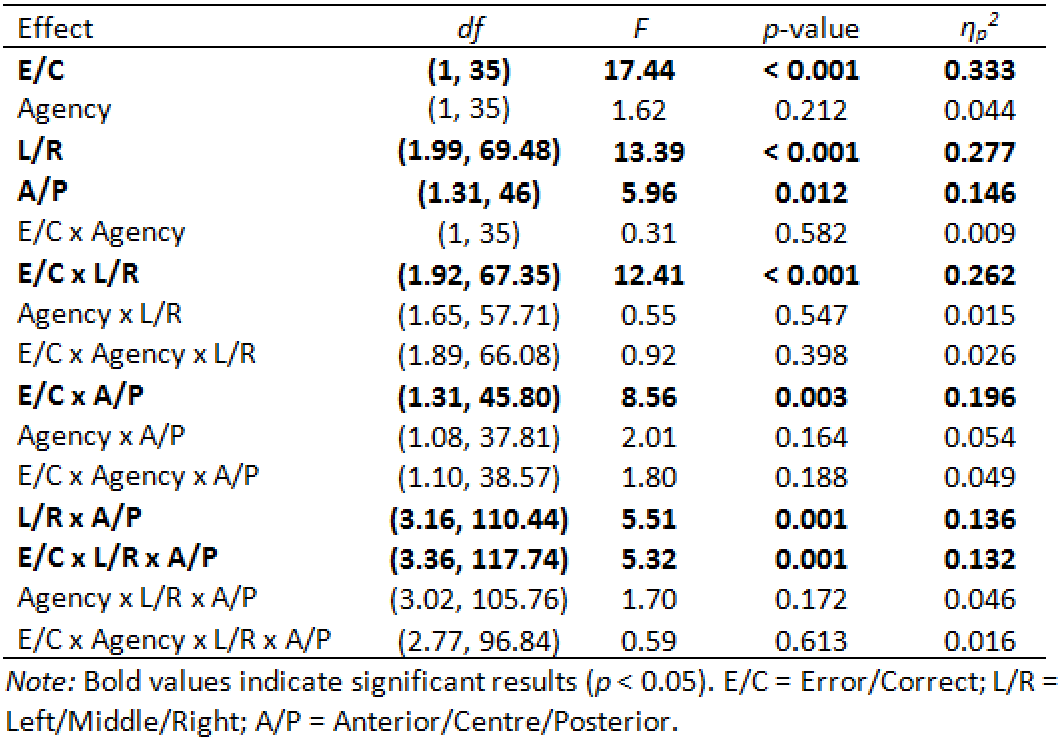


Figure 2.12. Upper – Grand-averaged waveforms showing the Pe (120 – 230 ms, shaded) during self performance time-locked to onset of correct (blue) and error (red) keystrokes at electrode FCz. The solid lines represent playing in the unambiguous condition, dashed lines represent playing in the ambiguous condition. Lower – Scalp voltage distributions for each condition at 170 ms.

A 2 x 2 x 3 x 3 (Error/Correct x Agency x Lateralisation [left/middle/right] x Anterior/Posterior [anterior/centre/posterior]) ANOVA was performed on the Pe. Full ANOVA results are shown in Table 2.21. This analysis yielded a main effect of Error/Correct ($F(1, 35) = 17.44$, $p < 0.001$), a main effect of Lateralisation ($F(1.99, 69.48) = 13.39$, $p < 0.001$), a main effect of Anterior/Posterior ($F(1.31, 45.99) = 5.96$, $p = 0.012$), an interaction of Error/Correct and Lateralisation ($F(1.92, 67.35) = 12.41$, $p < 0.001$), an interaction of Error/Correct and Anterior/Posterior ($F(1.31, 45.80) = 8.56$, $p = 0.003$), an interaction of Lateralisation and Anterior/Posterior ($F(3.16, 110.44) = 5.51$, $p = 0.001$), and a 3-way interaction between Error/Correct, Lateralisation, and Anterior/Posterior ($F(3.36, 117.74) = 5.32$, $p = 0.001$).

Table 2.21

ANOVA values for analysis of Pe during performance of error and correct keystrokes at a time window of 120 – 230 ms with factors of Error/Correct x Agency x Lateralization x Anterior/Posterior.



Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 35)**	**17.44**	**< 0.001**	**0.333**
Agency	(1, 35)	1.62	0.212	0.044
L/R	**(1.99, 69.48)**	**13.39**	**< 0.001**	**0.277**
A/P	**(1.31, 46)**	**5.96**	**0.012**	**0.146**
E/C x Agency	(1, 35)	0.31	0.582	0.009
E/C x L/R	**(1.92, 67.35)**	**12.41**	**< 0.001**	**0.262**
Agency x L/R	(1.65, 57.71)	0.55	0.547	0.015
E/C x Agency x L/R	(1.89, 66.08)	0.92	0.398	0.026
E/C x A/P	**(1.31, 45.80)**	**8.56**	**0.003**	**0.196**
Agency x A/P	(1.08, 37.81)	2.01	0.164	0.054
E/C x Agency x A/P	(1.10, 38.57)	1.80	0.188	0.049
L/R x A/P	**(3.16, 110.44)**	**5.51**	**0.001**	**0.136**
E/C x L/R x A/P	**(3.36, 117.74)**	**5.32**	**0.001**	**0.132**
Agency x L/R x A/P	(3.02, 105.76)	1.70	0.172	0.046
E/C x Agency x L/R x A/P	(2.77, 96.84)	0.59	0.613	0.016

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct; L/R = Left/Middle/Right; A/P = Anterior/Centre/Posterior.

Breaking the ANOVA down by Anterior/Posterior showed effects at each level of Anterior, Centre, and Posterior regions of interest (see Figure 2.13). In the Anterior regions of interest, the analysis revealed a main effect of Error/Correct ($F(1, 35) = 18.48$, $p < 0.001$), a main effect of Lateralisation ($F(1.89, 65.40) = 9.84$, $p < 0.001$), and an interaction between Error/Correct and Lateralisation ($F(2, 69.26) = 7.51$, $p = 0.001$). Full ANOVA results are shown in Table 2.22. Amplitude of the Pe was larger when playing error keystrokes than when playing correct keystrokes, regardless of Agency or Lateralisation ($t(35) = 4.30$, $p < 0.001$; see Figure 2.13).

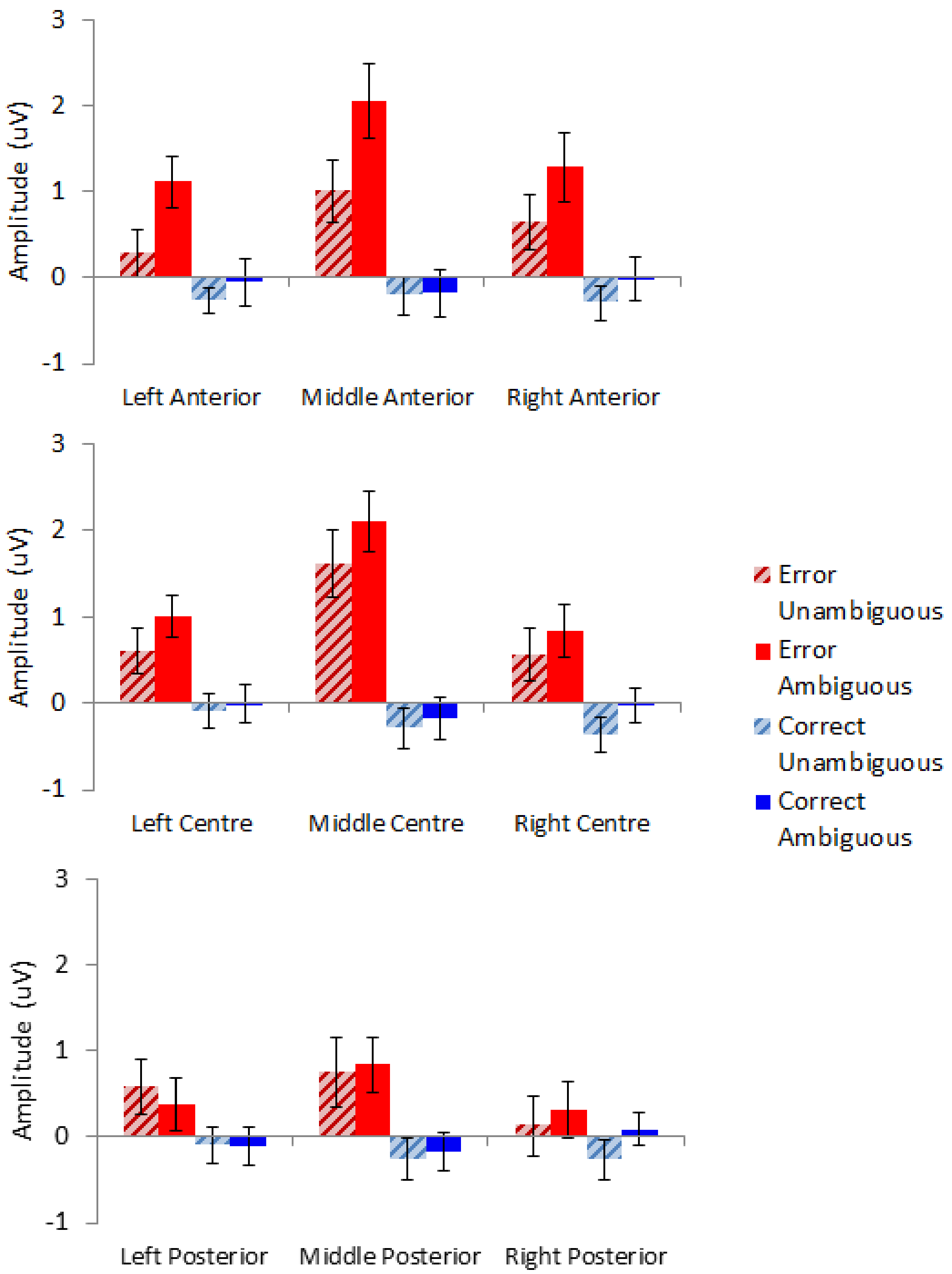


Figure 2.13. Amplitude (in microvolts) of Pe for regions of interest time-locked to error and correct keystrokes in ambiguous and unambiguous conditions of agency.

Table 2.22

ANOVA values for analysis of Pe during performance of error and correct keystrokes at a time window of 120 – 230 ms with factors of Error/Correct x Agency x Lateralization for Anterior regions of interest.

Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 35)**	**18.48**	**< 0.001**	**0.346**
Agency	(1, 35)	3.07	0.089	0.081
L/R	**(1.89, 65.40)**	**9.84**	**< 0.001**	**0.219**
E/C x Agency	(1, 35)	1.92	0.175	0.052
E/C x L/R	**(2, 69.26)**	**7.51**	**0.001**	**0.177**
Agency x L/R	(1.84 64.49)	0.16	0.838	0.004
E/C x Agency x L/R	(1.61, 56.25)	1.50	0.234	0.041

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct; L/R = Left/Middle/Right.

In the Centre regions of interest, there was a main effect of Error/Correct ($F(1, 35) = 22.80$, $p < 0.001$), a main effect of Lateralisation ($F(1.98, 69.45) = 17.82$, $p < 0.001$), and an interaction between Error/Correct and Lateralisation ($F(1.89, 65.99) = 16.90$, $p < 0.001$). Full ANOVA results are shown in Table 2.23. Amplitude of the Pe was larger when playing error keystrokes than when playing correct keystrokes, regardless of Agency or Lateralisation ($t(35) = 4.78$, $p < 0.001$; see Figure 2.13).

Table 2.23

ANOVA values for analysis of Pe during performance of error and correct keystrokes at a time window of 120 – 230 ms with factors of Error/Correct x Agency x Lateralization for Centre regions of interest.

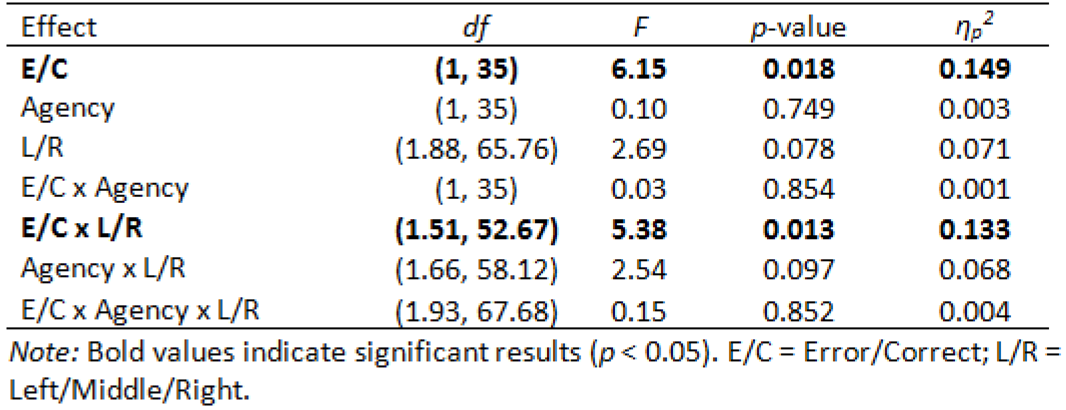
Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 35)**	**22.80**	**< 0.001**	**0.394**
Agency	(1, 35)	1.56	0.22	0.043
L/R	**(1.98, 69.45)**	**17.82**	**< 0.001**	**0.337**
E/C x Agency	(1, 35)	0.22	0.642	0.006
E/C x L/R	**(1.89, 65.99)**	**16.90**	**< 0.001**	**0.326**
Agency x L/R	(1.77, 61.99)	0.13	0.855	0.004
E/C x Agency x L/R	(1.74, 60.88)	0.66	0.502	0.018

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct; L/R = Left/Middle/Right.

In the Posterior regions of interest, there was a main effect of Error/Correct ($F(1, 35) = 6.147$, $p = 0.018$) and an interaction between Error/Correct and Lateralisation ($F(1.51, 52.67) = 5.38$, $p = 0.013$). Full ANOVA results are shown in Table 2.24. Amplitude of the Pe was larger when playing error keystrokes than when playing correct keystrokes in the left posterior ($t(35) = 2.27$, $p = 0.029$) and middle posterior ($t(35) = 3.17$, $p = 0.003$) regions of interest, regardless of Agency condition, but not in the right posterior region of interest ($t(35) = 1.15$, $p = 0.256$; see Figure 2.13).

Table 2.24

ANOVA values for analysis of Pe during performance of error and correct keystrokes at a time window of 120 – 230 ms with factors of Error/Correct x Agency x Lateralization for Posterior regions of interest.



Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 35)**	**6.15**	**0.018**	**0.149**
Agency	(1, 35)	0.10	0.749	0.003
L/R	(1.88, 65.76)	2.69	0.078	0.071
E/C x Agency	(1, 35)	0.03	0.854	0.001
E/C x L/R	**(1.51, 52.67)**	**5.38**	**0.013**	**0.133**
Agency x L/R	(1.66, 58.12)	2.54	0.097	0.068
E/C x Agency x L/R	(1.93, 67.68)	0.15	0.852	0.004

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct; L/R = Left/Middle/Right.

2.3.2.3 Feedback-related Negativity

The FRN, which was predicted to be elicited by errors performed by a partner, was observed between 215 – 300 ms, with a more parietal distribution than the ERN or Pe (see Figure 2.14). The 2 x 2 x 3 x 3 (Error/Correct x Agency x Lateralisation [left/middle/right] x Anterior/Posterior [anterior/centre/posterior]) ANOVA yielded a main effect of Error ($F(1, 35) =$

5.91, $p = 0.02$) and a main effect of Anterior/Posterior ($F(1.20, 42.03) = 5.72$, $p = 0.016$). Full ANOVA results are shown in Table 2.25.

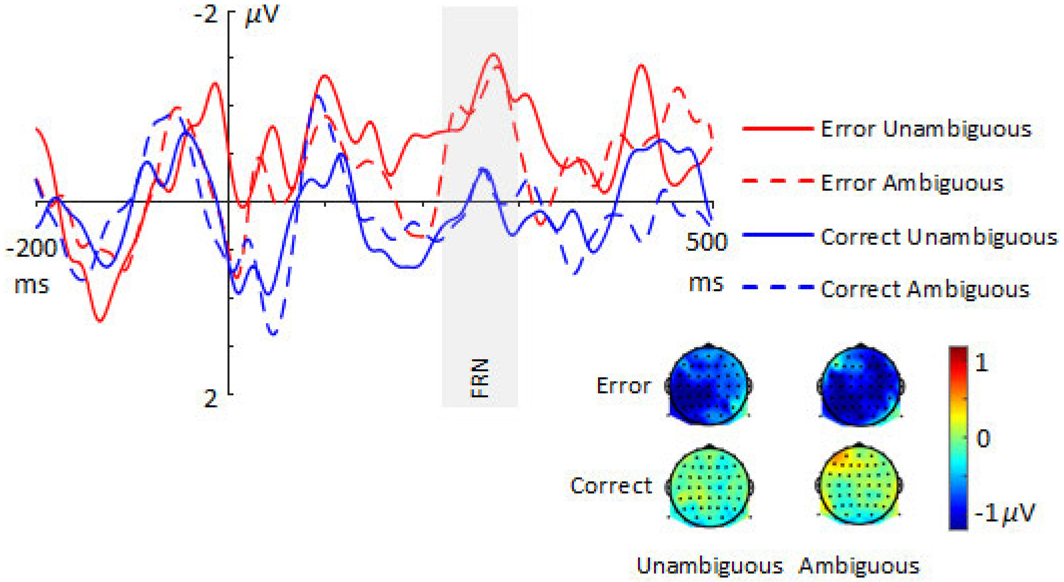


Figure 2.14. Upper – Grand-averaged waveforms showing the FRN (215 – 300 ms, shaded) during self performance time-locked to onset of correct (blue) and error (red) keystrokes at electrode CPz. The solid lines represent playing in the unambiguous condition, dashed lines represent playing in the ambiguous condition. Lower – Scalp voltage distributions for each condition at 275 ms.

Table 2.25

ANOVA values for analysis of FRN during performance of error and correct keystrokes at a time window of 215 – 300 ms with factors of Error/Correct x Agency x Lateralization x Anterior/Posterior.

Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 35)**	**5.91**	**0.02**	**0.144**
Agency	(1, 35)	0.17	0.684	0.005
L/R	(1.80, 63.04)	1.08	0.339	0.03
A/P	**(1.20, 42.03)**	**5.72**	**0.016**	**0.14**
E/C x Agency	(1, 35)	0.08	0.775	0.002
E/C x L/R	(1.82, 63.58)	2.51	0.095	0.067
Agency x L/R	(1.62, 56.69)	0.53	0.555	0.015
E/C x Agency x L/R	(1.65, 57.88)	0.66	0.496	0.018
E/C x A/P	(1.24, 43.22)	0.98	0.347	0.027
Agency x A/P	(1.29, 44.99)	0.59	0.486	0.017
E/C x Agency x A/P	(1.32, 46.14)	0.58	0.495	0.016
L/R x A/P	(3.11, 108.69)	2.47	0.064	0.066
E/C x L/R x A/P	(2.86, 100.24)	0.91	0.434	0.025
Agency x L/R x A/P	(2.43, 85.05)	1.76	0.17	0.048
E/C x Agency x L/R x A/P	(2.97, 103.96)	0.75	0.524	0.021

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct; L/R = Left/Middle/Right; A/P = Anterior/Centre/Posterior.

Breaking the ANOVA down by Anterior/Posterior revealed significant effects in the Centre and Posterior regions of interest (see Figure 2.15). In the Centre regions of interest, there was a main effect of Error/Correct ($F(1, 35) = 6.99$, $p = 0.012$). Full ANOVA results are shown in Table 2.26. The amplitude of the FRN was more negative when playing error keystrokes than when playing correct keystrokes, regardless of Agency or Lateralisation ($t(35) = 2.64$, $p = 0.012$).

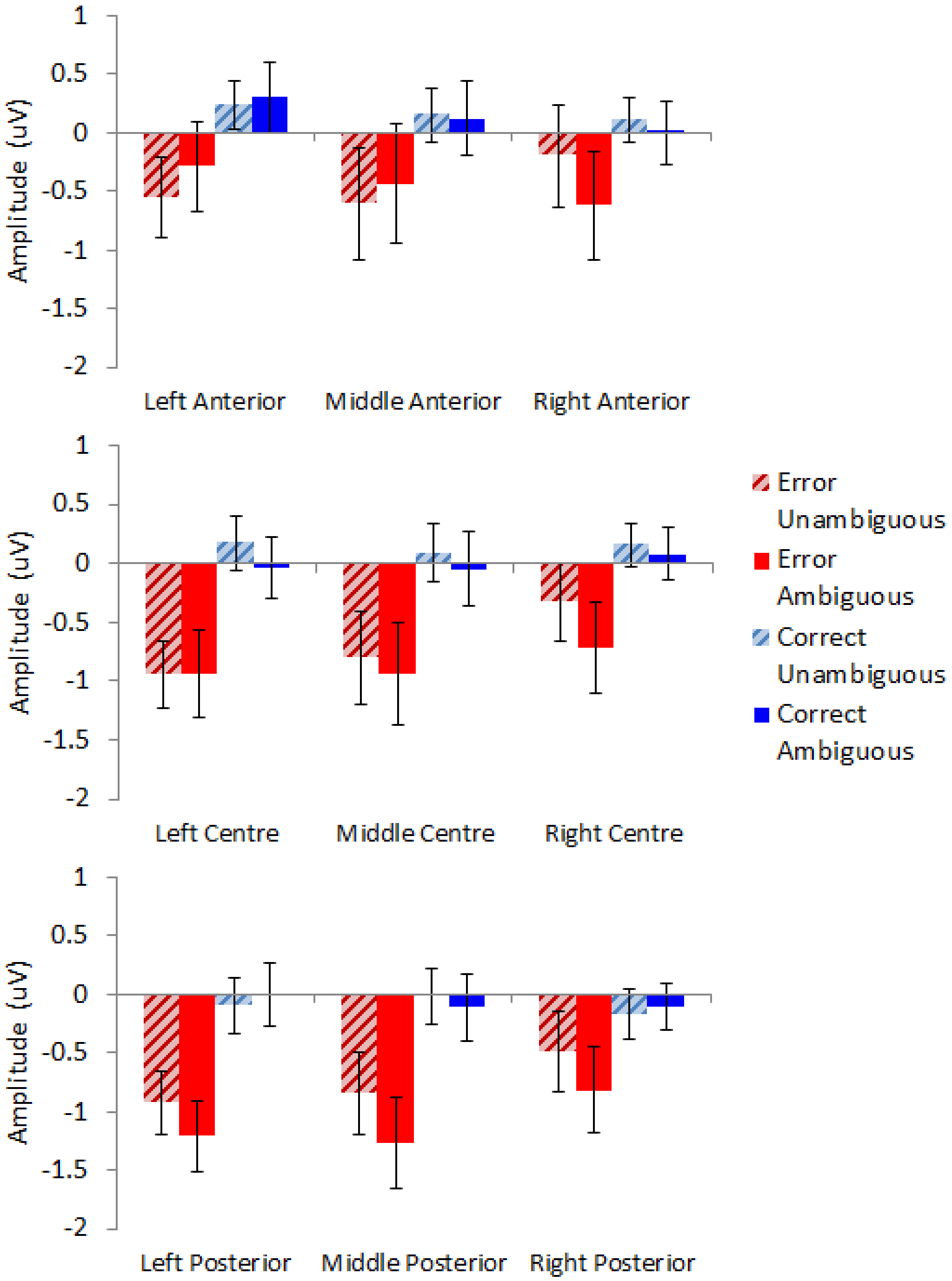


Figure 2.15. Amplitude (in microvolts) of FRN for regions of interest time-locked to error and correct keystrokes in ambiguous and unambiguous conditions of agency.

Table 2.26

ANOVA values for analysis of FRN during performance of error and correct keystrokes at a time window of 215 – 300 ms with factors of Error/Correct x Agency x Lateralization for Centre regions of interest.

Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 35)**	**6.99**	**0.012**	**0.166**
Agency	(1, 35)	0.30	0.588	0.008
L/R	(1.90, 66.33)	2.23	0.0118	0.060
E/C x Agency	(1, 35)	0.004	0.948	0.000
E/C x L/R	(1.77, 61.99)	1.52	0.227	0.042
Agency x L/R	(1.75, 61.13)	0.23	0.763	0.007
E/C x Agency x L/R	(1.48, 51.61)	0.97	0.363	0.027

Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct; L/R = Left/Middle/Right.

In the Posterior regions of interest, there was a main effect of Error/Correct ($F(1, 35) = 7.11$, $p = 0.012$) and an interaction between Error/Correct and Lateralisation ($F(1.96, 68.70) = 4.88$, $p = 0.011$). Full ANOVA results are shown in Table 2.27. The FRN was significantly more negative when playing error keystrokes than when playing correct keystrokes in the left posterior ($t(35) = 3.35$, $p = 0.002$) and middle posterior ($t(35) = 2.692$, $p = 0.011$) regions of interest, regardless of Agency condition, but not in the right posterior region of interest ($t(35) = 1.602$, $p = 0.118$; see Figure 2.15).

Table 2.27

ANOVA values for analysis of FRN during performance of error and correct keystrokes at a time window of 215 – 300 ms with factors of Error/Correct x Agency x Lateralization for Posterior regions of interest.

Effect	*df*	*F*	*p*-value	η_p^2
E/C	**(1, 35)**	**7.11**	**0.012**	**0.169**
Agency	(1, 35)	0.36	0.552	0.010
L/R	(1.84, 64.25)	1.68	0.196	0.046
E/C x Agency	(1, 35)	0.68	0.416	0.019
E/C x L/R	**(1.96, 68.70)**	**4.88**	**0.011**	**0.122**
Agency x L/R	(1.79, 62.61)	0.31	0.708	0.009
E/C x Agency x L/R	(1.79, 62.59)	0.02	0.969	0.001

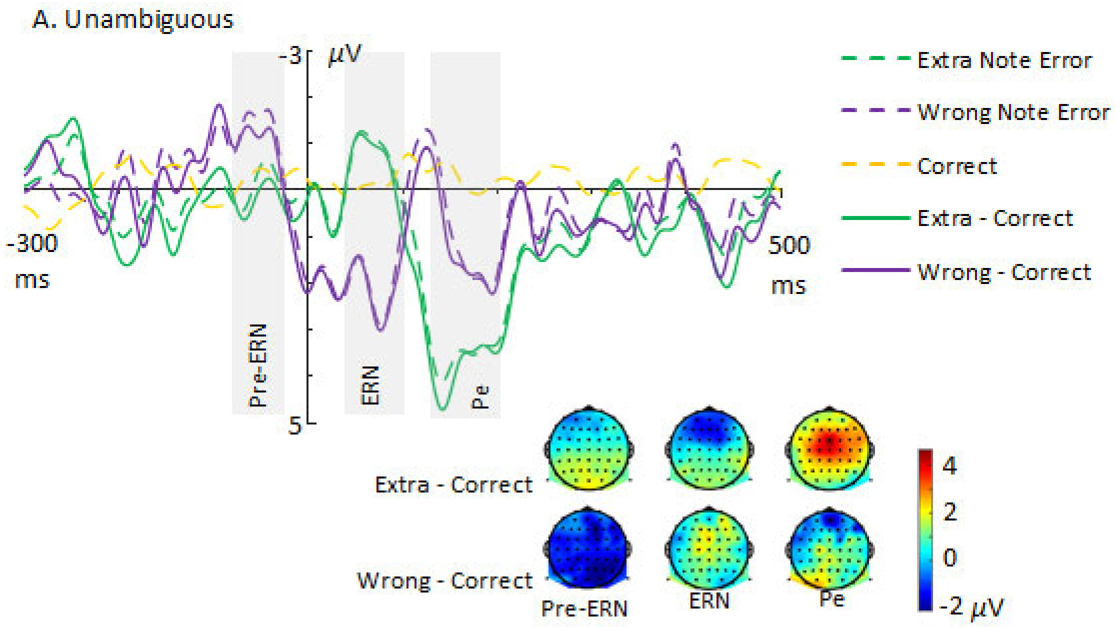
Note: Bold values indicate significant results ($p < 0.05$). E/C = Error/Correct; L/R = Left/Middle/Right.

2.3.2.4 Extra Note Errors vs. Wrong Note Errors

As there was a difference in behavioural results depending on error type, the EEG data was likewise split by error type (extra note errors and wrong note errors) and analyses were performed on the split data. Previous piano studies reported a pre-ERN occurring 50 ms prior to error onset (Maidhof et al., 2009; Ruiz et al., 2009) and the errors used in their analyses were wrong note errors. Because of this, the time window of -80 to -25 ms was analysed for the data split by error type.

Error-related Negativity

The ERN was expected to be observed for both extra note and wrong note errors, but perhaps at different latencies because of the difference in error processing between these error types. Figure 2.16 shows the ERN for extra note error sequences, wrong note error sequences, and correct sequences.



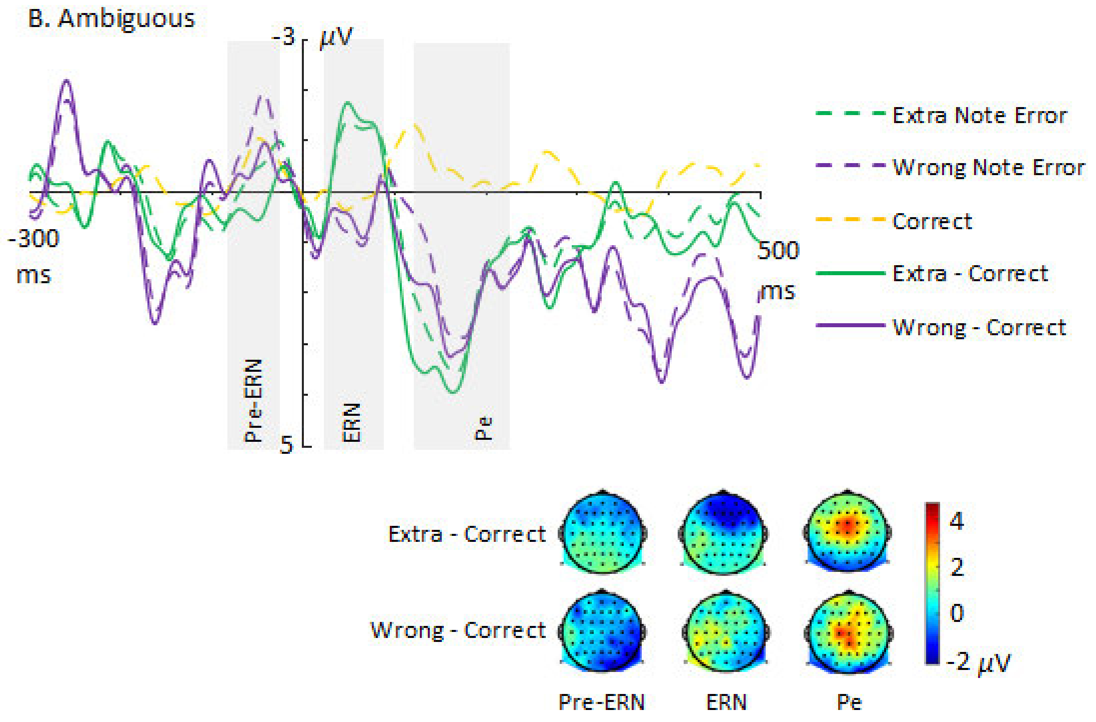


Figure 2.16. Grand-averaged waveforms showing pre-ERN (-80 to -25 ms), ERN (30 to 90 ms), and Pe (120 to 230 ms) time-locked to onset of self-produced extra note errors (green dashed), wrong note errors (purple dashed), and correct notes (yellow dashed) for unambiguous (A.) and ambiguous (B.) trials at electrode FCz. Solid lines show difference waves for extra note errors minus correct (green solid) and wrong note errors minus correct (purple solid). Shown below each waveform plot are the respective scalp voltage distributions for difference waves for pre-ERN (at -60 ms), ERN (at 60 ms), and Pe (at 150 ms) components. *NB*: Wrong note errors had a low number of trials.

A 3 x 2 x 3 x 3 (Extra/Wrong/Correct x Agency x Lateralisation [left/middle/right] x Anterior/Posterior [anterior/centre/posterior]) ANOVA was performed on the time window of 30 – 90 ms. Results showed a significant main effect of Anterior/Posterior (F(1.22, 31.63) = 4.22, p = 0.041), an interaction between Extra/Wrong/Correct and Anterior/Posterior (F(1.70, 44.15) = 4.69, p = 0.019) and an interaction between Extra/Wrong/Correct, Lateralisation, and Anterior/Posterior (F(3.67, 95.47) = 2.90, p = 0.03). Full ANOVA results are shown in Table 2.28. There were no significant results involving agency, thus remaining analyses were carried out on data collapsed across agency conditions.

Table 2.28
ANOVA values for analysis of ERN during performance of error and correct keystrokes at a time window of 30 – 90 ms with factors of Extra error/Wrong error/Correct x Agency x Lateralization x Anterior/Posterior.

Effect	*df*	*F*	*p*-value	η_p^2
E/W/C	(1.36, 35.35)	0.34	0.633	0.013
Agency	(1, 26)	0.60	0.447	0.022
L/R	(1.65, 42.87)	0.10	0.869	0.004
A/P	**(1.22, 31.63)**	**4.22**	**0.041**	**0.14**
E/W/C x Agency	(1.35, 35.01)	0.55	0.513	0.021
E/W/C x L/R	(2.44, 63.48)	2.49	0.08	0.087
Agency x L/R	(2, 51.87)	0.11	0.895	0.004
E/W/C x Agency x L/R	(2.66, 69.06)	0.68	0.553	0.025
E/W/C x A/P	**(1.70, 44.15)**	**4.69**	**0.019**	**0.153**
Agency x A/P	(1.19, 30.95)	0.23	0.676	0.009
E/W/C x Agency x A/P	(1.87, 48.53)	0.21	0.796	0.008
L/R x A/P	(2.72, 70.75)	1.72	0.176	0.062
E/W/C x L/R x A/P	**(3.67, 95.47)**	**2.90**	**0.03**	**0.1**
Agency x L/R x A/P	(2.71, 70.52)	0.33	0.787	0.012
E/W/C x Agency x L/R x A/P	(3.79, 98.41)	1.14	0.342	0.042

Note: Bold values indicate significant results (p < 0.05). E/W/C = Extra error/Wrong error/Correct; L/R = Left/Middle/Right; A/P = Anterior/Centre/Posterior.

Breaking the ANOVA down by Anterior/Posterior revealed significant results in the Anterior and Centre regions of interest (see Figure 2.17). In the Anterior regions of interest, there was a significant interaction between Lateralisation and Extra/Wrong/Correct ($F(2.53, 65.74) = 3.03$, $p = 0.437$), but no significant main effects (Lateralisation: $F(1.95, 50.81) = 0.84$, $p = 0.044$; Extra/Wrong/Correct: $F(1.73, 45.07) = 2.35$, $p = 0.114$). Amplitude of the ERN more negative when playing extra note errors than when playing wrong note errors ($t(26) = 2.86$, $p = 0.008$) or when playing correct notes ($t(26) = 2.258$, $p = 0.003$) in the middle anterior region of interest only (see Figure 2.17).

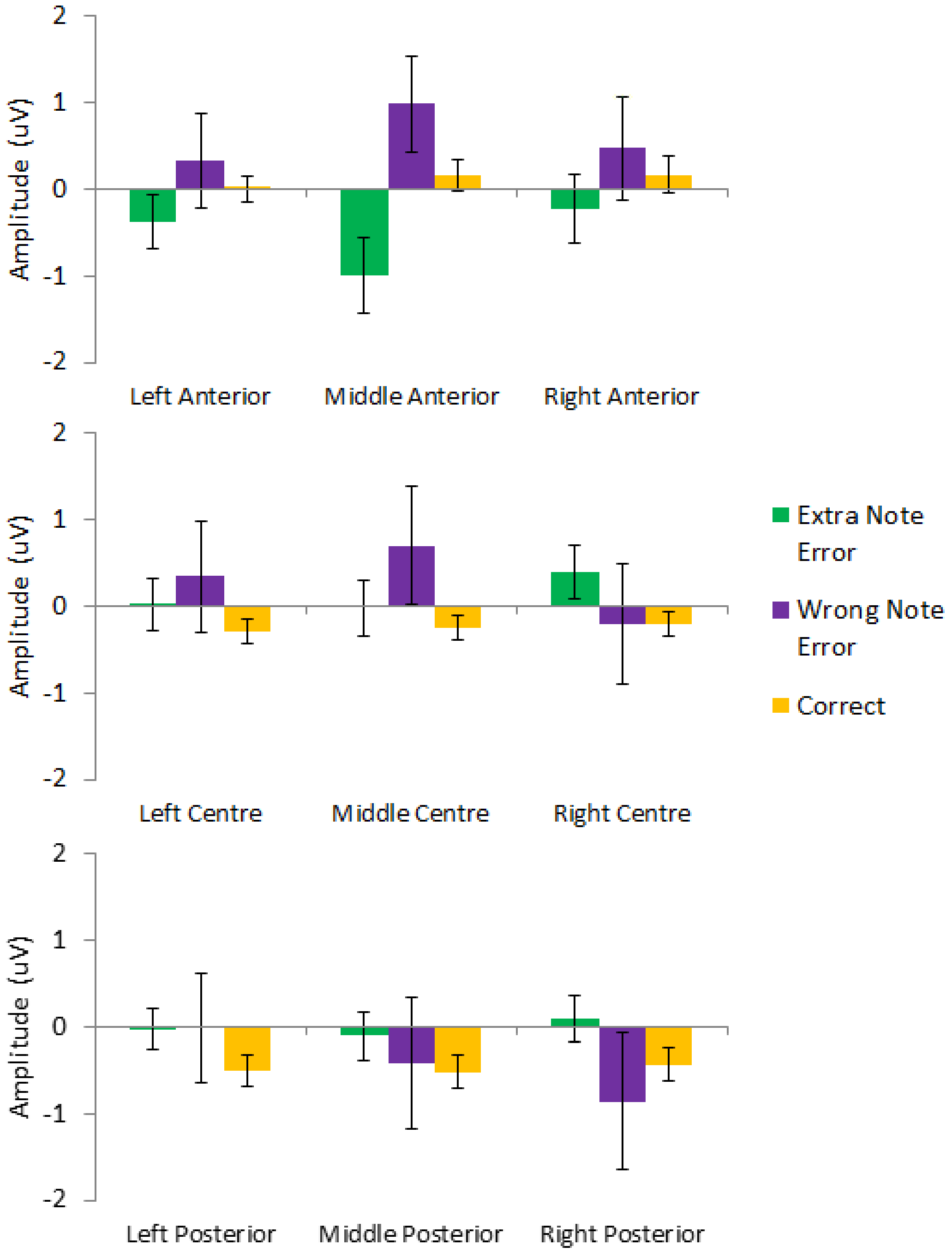


Figure 2.17. Amplitude (in microvolts) of ERN for regions of interest time-locked to extra note errors, wrong note errors, and correct keystrokes.

In the Centre regions of interest, there was a significant interaction between Lateralisation and Extra/Wrong/Correct ($F(2.73, 70.95) = 2.95$, $p = 0.043$), but no significant main effects (Lateralisation: $F(1.67, 43.46) = 0.54$, $p =$

0.554; Extra/Wrong/Correct: $F(1.33, 34.66) = 0.48$, $p = 0.545$). However, further analyses revealed no significant differences between extra note errors, wrong note errors, and correct notes in any of the lateralized position (left, middle, or right; all p-values > 0.05). Analyses on the differences between the condition revealed that the difference between extra note errors and wrong note errors was significantly greater in the right centre region of interest than in the middle centre region of interest ($t(26) = -2.63$, $p = 0.014$) and the difference between wrong note errors and correct notes was significantly greater in the middle centre region of interest than in the right centre region of interest ($t(26) = 2.88$, $p = 0.008$; see Figure 2.17).

Pre-Error-Related Negativity

As the previous piano studies only analysed wrong note errors (Maidhof et al., 2009; Ruiz et al., 2009), the error type analysis was expected to show the pre-ERN for wrong note errors (see Figure 2.16). A 3 x 2 x 3 x 3 (Extra/Wrong/Correct x Agency x Lateralisation [left/middle/right] x Anterior/Posterior [anterior/centre/posterior]) ANOVA was conducted on the time window of 80 – 25 ms prior to the error onset. There was a significant main effect of Extra/Wrong/Correct ($F(1.57, 40.87) = 4.48$, $p = 0.025$), a significant interaction between Extra/Wrong/Correct and Lateralisation ($F(2.87, 74.62) = 2.90$, $p = 0.043$), and a significant interaction between Extra/Wrong/Correct and Anterior/Posterior ($F(2.17, 56.33) = 7.12$, $p = 0.001$). There was no significant main effect of Agency or interactions involving Agency. Full ANOVA results are shown in Table 2.29. There were no significant results involving agency, thus remaining analyses were carried out on data collapsed across agency conditions.

Table 2.29
ANOVA values for analysis of pre-ERN during performance of error and correct keystrokes at a time window of 50 –20 ms pre-error onset with factors of Extra error/Wrong error/Correct x Agency x Lateralization x Anterior/Posterior.

Effect	*df*	*F*	*p*-value	η_p^2
E/W/C	**(1.57, 40.87)**	**4.48**	**0.025**	**0.147**
Agency	(1, 26)	0.00	0.966	0
L/R	(1.49, 38.72)	2.03	0.156	0.072
A/P	(1.22, 31.83)	2.26	0.138	0.08
E/W/C x Agency	(1.26, 32.68)	0.25	0.675	0.009
E/W/C x L/R	**(2.87, 74.62)**	**2.90**	**0.043**	**0.1**
Agency x L/R	(1.88, 48.96)	1.01	0.368	0.037
E/W/C x Agency x L/R	(3.34, 86.93)	0.57	0.652	0.022
E/W/C x A/P	**(2.17, 56.33)**	**7.12**	**0.001**	**0.215**
Agency x A/P	(1.42, 36.89)	0.25	0.707	0.009
E/W/C x Agency x A/P	(1.55, 40.34)	0.12	0.832	0.005
L/R x A/P	(2.65, 68.76)	1.49	0.228	0.054
E/W/C x L/R x A/P	(3.21, 83.53)	1.04	0.382	0.038
Agency x L/R x A/P	(3.33, 86.65)	0.35	0.812	0.013
E/W/C x Agency x L/R x A/P	(3.54, 91.96)	0.79	0.519	0.03

Note: Bold values indicate significant effects ($p < 0.05$). E/W/C = Extra note error/Wrong note error/Correct note; L/R = Left/Middle/Right; A/P = Anterior/Centre/Posterior.

Breaking the ANOVA down by Lateralisation revealed significant effects in all lateralised regions of interest (see Figure 2.18). In the Left region of interest, there was a significant interaction between Anterior/Posterior and Extra/Wrong/Correct ($F(1.86, 48.47) = 4.06$, $p = 0.026$), but no significant main effect of Extra/Wrong/Correct ($F(1.42, 37.01) = 3.51$, $p = 0.055$) or Anterior/Posterior ($F(1.22, 31.68) = 2.8$, $p = 0.097$). In the Left Posterior region of interest, amplitude of the pre-ERN was more negative when playing wrong note errors ($t(26) = 2.76$, $p = 0.011$) and when playing correct notes ($t(26) = 3.64$, $p = 0.001$) than when playing extra note errors, but no significant difference was found between wrong note errors and correct notes ($t(26) = 0.94$, $p = 0.335$).

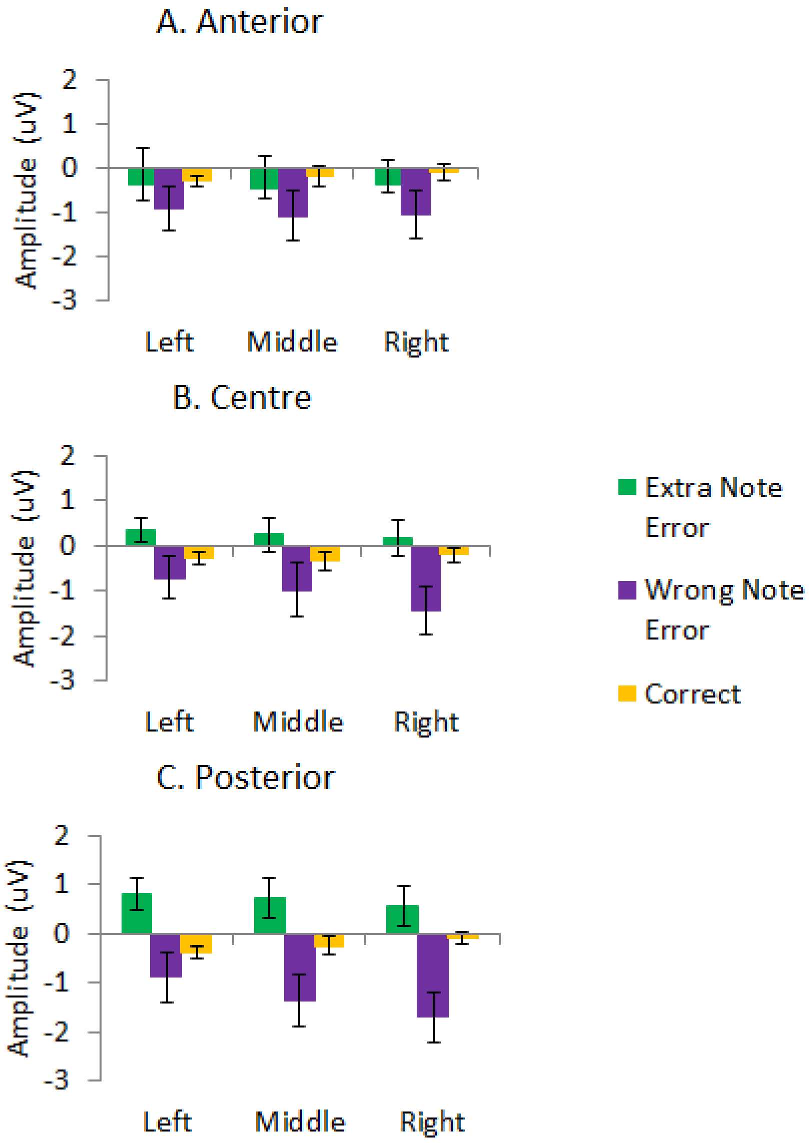


Figure 2.18. Amplitude (in microvolts) of pre-ERN for regions of interest time-locked to extra note errors, wrong note errors, and correct keystrokes.

In the Middle regions of interest, there was a significant interaction between Anterior/Posterior and Extra/Wrong/Correct ($F(2.12, 55.03) = 5.73$, $p = 0.005$), but no significant main effect of Extra/Wrong/Correct ($F(1.64, 42.72) =$

3.31, *p* = 0.055) or Anterior/Posterior (*F*(1.21, 31.52) = 1.36, *p* = 0.26). In the Middle Posterior region of interest, amplitude of the pre-ERN was more negative when playing wrong note errors (*t*(26) = 3.57, *p* = 0.001) and when playing correct notes (*t*(26) = 2.38, *p* = 0.025) than when playing extra note errors, but no significant difference was found between wrong note errors and correct notes (*t*(26) = 1.92, *p* = 0.066; see Figure 2.18).

Finally, in the Right regions of interest, there was a significant main effect of Extra/Wrong/Correct (*F*(1.71, 44.56) = 5.53, *p* = 0.01) and a significant interaction between Anterior/Posterior and Extra/Wrong/Correct (*F*(2.1, 54.63) = 5.76, *p* = 0.005), but no significant main effect of Anterior/Posterior (*F*(1.22, 31.82) = 0.27, *p* = 0.653). In the Right Centre region of interest, amplitude of the pre-ERN when playing wrong note errors was more negative than when playing extra note errors (*t*(26) = 2.68, *p* = 0.013) or when playing correct notes (*t*(26) = 2.28, *p* = 0.031), but there was no significant difference found between extra note errors and correct notes (*t*(26) = 0.90, *p* = 0.378). Likewise, in the Right Posterior region of interest, amplitude of the pre-ERN when playing wrong note errors was more negative than when playing extra note errors (*t*(26) = 3.75, *p* = 0.001) or when playing correct notes (*t*(26) = 2.98, *p* = 0.006), but no significant difference was found between extra note errors and correct notes (*t*(26) = 1.62, *p* = 0.117; see Figure 2.18).

Error Positivity

The Pe component was not expected to be different for error type, so it was expected that activity when playing both extra note errors and wrong note errors would show greater amplitudes in the P300 component than when playing correct notes (see Figure 2.16). The 3 x 2 x 3 x 3 (Extra/Wrong/Correct x Agency x Lateralisation [left/middle/right] x Anterior/Posterior [anterior/centre/posterior]) ANOVA at the time window of 120 – 230 ms revealed a significant main effect of Lateralisation (*F*(1.93, 50.18) = 9.37, $p <$ 0.001), a significant interaction between Extra/Wrong/Correct and Anterior/Posterior (*F*(1.53, 39.73) = 5.40, p = 0.014), and a significant interaction between Lateralisation and Anterior/Posterior (*F*(2.62, 68.19) = 6.14, p = 0.002). Full ANOVA results are shown in Table 2.30. There were no significant results involving agency, thus remaining analyses were carried out on data collapsed across agency conditions.

Table 2.30

ANOVA values for analysis of Pe during performance of error and correct keystrokes at a time window of 120 –230 ms with factors of Extra error/Wrong error/Correct x Agency x Lateralization x Anterior/Posterior.

Effect	*df*	*F*	*p*-value	η_p^2
E/W/C	(1.30, 33.80)	2.77	0.096	0.096
Agency	(1, 26)	0.02	0.902	0.001
L/R	**(1.93, 50.18)**	**9.37**	**< 0.001**	**0.265**
A/P	(1.27, 33.00)	3.45	0.063	0.117
E/W/C x Agency	(1.56, 40.43)	0.53	0.55	0.02
E/W/C x L/R	(2.47, 64.20)	2.40	0.088	0.084
Agency x L/R	(1.57, 40.87)	0.45	0.595	0.017
E/W/C x Agency x L/R	(1.97, 51.22)	0.66	0.52	0.025
E/W/C x A/P	**(1.53, 39.73)**	**5.40**	**0.014**	**0.172**
Agency x A/P	(1.10, 28.54)	3.04	0.089	0.105
E/W/C x Agency x A/P	(2.04, 53.10)	3.02	0.056	0.104
L/R x A/P	**(2.62, 68.19)**	**6.14**	**0.002**	**0.191**
E/W/C x L/R x A/P	(4.78, 124.14)	1.44	0.216	0.053
Agency x L/R x A/P	(2.89, 75.21)	0.10	0.958	0.004
E/W/C x Agency x L/R x A/P	(4.13, 107.49)	0.64	0.64	0.024

Note: Bold values indicate significant results ($p < 0.05$). E/W/C = Extra error/Wrong error/Correct; L/R = Left/Middle/Right; A/P = Anterior/Centre/Posterior.

Breaking the ANOVA down by Anterior/Posterior revealed significant effects in Anterior, Centre, and Posterior regions of interest (see Figure 2.19). In the Anterior regions of interest, there was a significant main effect of Lateralisation ($F(1.92, 49.83) = 5.94$, $p = 0.005$) and a significant main effect of Extra/Wrong/Correct ($F(1.53, 39.88) = 3.94$, $p = 0.037$) but no significant interaction ($F(2.24, 58.15) = 1.15$, $p = 0.328$). Amplitude of the Pe was greater when playing extra note errors than when playing correct notes ($t(26) = 4.62$, $p < 0.001$) in the Middle Anterior region of interest, but there were no significant differences between extra note errors and wrong note errors ($t(26) = 1.44$, $p = 0.162$) or between wrong note errors and correct notes ($t(26) = 1.22$, $p = 0.223$).

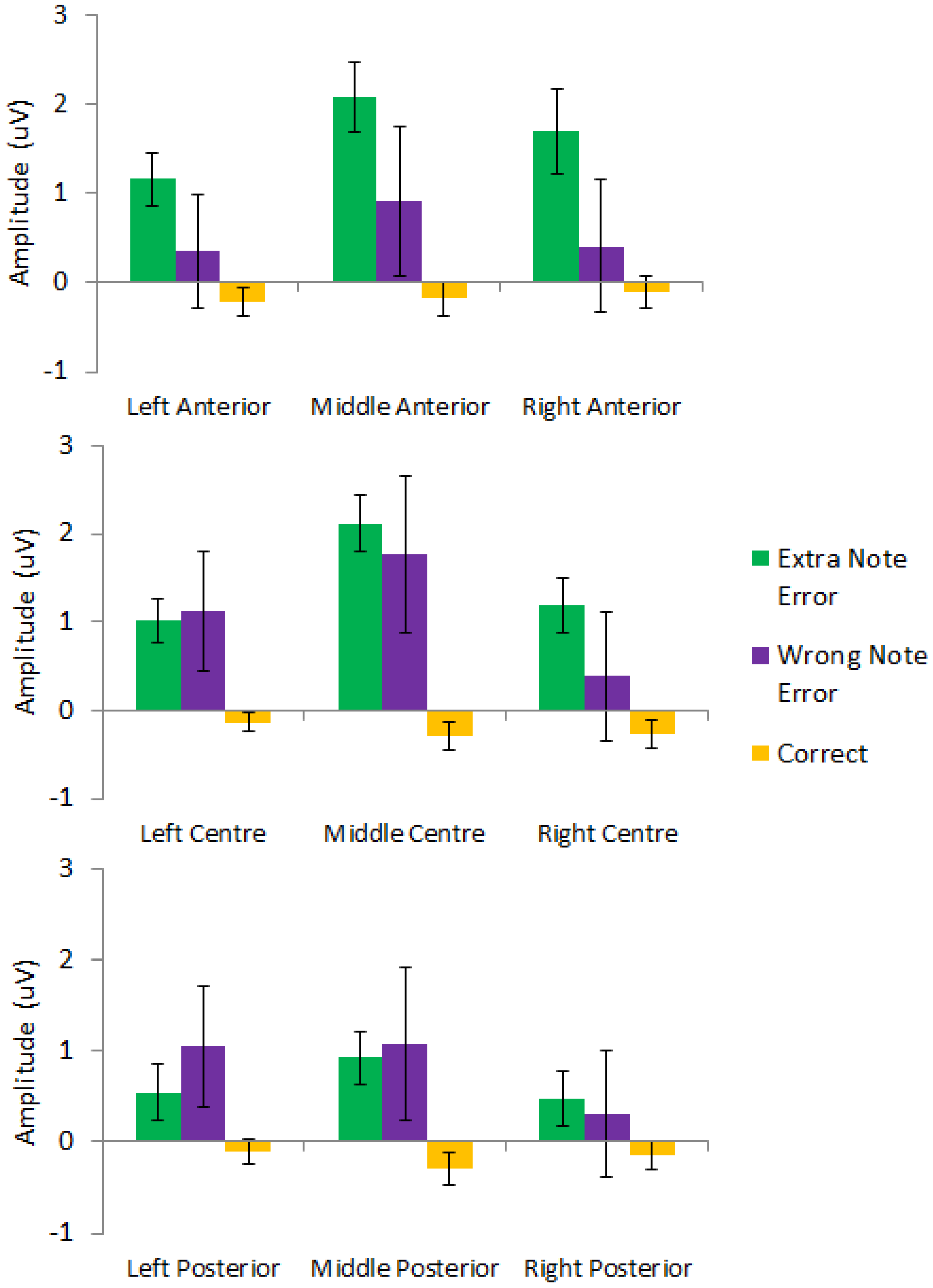


Figure 2.19. Amplitude (in microvolts) of Pe for regions of interest time-locked to extra note errors, wrong note errors, and correct keystrokes.

In the Centre regions of interest, there was a significant main effect of Lateralisation ($F(1.75, 45.51) = 13.33$, $p < 0.001$), a significant main effect of Extra/Wrong/Correct ($F(1.27, 33.08) = 3.86$, $p = 0.049$), and a significant interaction between Lateralisation and Extra/Wrong/Correct ($F(2.59, 67.30) = 3.64$, $p = 0.022$). Amplitude of the Pe was greater when playing extra note errors than when playing correct notes ($t(26) = 5.69$, $p < 0.001$) and when playing wrong note errors than when playing correct notes ($t(26) = 2.12$, $p = 0.044$) in the Middle Centre region of interest, but there was no significant difference between extra note errors and wrong note errors ($t(26) = 0.44$, $p = 0.664$; see Figure 2.19).

In the Posterior regions of interest, there was a significant main effect of Lateralisation ($F(1.84, 47.75) = 3.38$, $p = 0.046$), but no significant main effect of Extra/Wrong/Correct ($F(1.24, 32.25) = 1.33$, $p = 0.267$) or significant interaction between Lateralisation and Extra/Wrong/Correct ($F(2.56, 66.60) = 1.85$, $p = 0.154$). Further analysis showed the amplitude of the Pe was greater in the Middle Posterior region of interest than the Right Posterior region of interest, regardless of error type ($t(26) = 2.911$, $p = 0.007$; see Figure 2.19).

2.4 Discussion

The current experiment set out to investigate behavioural and neural responses to naturally-occurring errors in a sequential and simultaneous joint action task in conditions that varied in agency ambiguity. To this end, pairs of highly skilled pianists simultaneously played piano pieces in unison (high ambiguity of agency) and octaves (low ambiguity of agency) as behavioural and neural measures were recorded. Analysis of IKI and MIDI keystroke velocity examined sequences of seven notes when the performer made an error and played correctly and when a partner made an error and played correctly. Analyses of ERPs examined self neural responses to one's own error compared to one's own correct playing and self neural responses to a partner's error compared to a partner's correct playing.

2.4.1 Behavioural Data

We expected to observe pre- and post-error slowing as in previous experiments involving piano performance (Maidhof et al., 2009; Ruiz et al., 2009). However, we observed pre-error speeding in self error sequences. To further understand this result, we split the data by error type – extra note errors and wrong note errors. This split showed that the pre-error speeding was driven by the extra note errors.

When playing extra note errors, participants played the pre-error note slightly late, perhaps causing them to rush the next note to keep time with their partner. Performers then played the error note and post-error note early, as reflected by shorter IKIs on these keystrokes. By the second post-error note, participants were back on pace with correct notes. Additionally, the pre-error and error keystrokes were played with less keystroke velocity than correct keystrokes and wrong note error keystrokes. This pattern of responses may be explained by the slip of a finger followed by an error correction. Participants played the pieces at a quick pace, which resulted in many finger slips. In these extra note error instances, the finger slipped from a correct note onto an error note and then made a quick correction. Further, these errors were almost always slips onto a neighbouring note, as is consistent with previous literature on errors in sequential performance (Palmer & Pfordresher, 2003; Palmer & van de Sande, 1993; Pfordresher, Palmer, & Jungers, 2007). In playing an extra note error, the performer made an error and followed it with a correction. Both the error and the correcting keystrokes were played quicker than the average correct keystroke. Participants were able to quickly correct the error within the timeframe of a single keystroke – they played two keystrokes (i.e., the error and the correction) within the time that it took to play an average correct keystroke. This allowed the erring partner to maintain synchrony with their partner on the subsequent notes even with correcting the error.

Wrong note errors showed a pattern of post-error slowing and reduced pre-error and error keystroke velocity. Compared to correct keystroke sequences and extra note error sequences, participants played the post-error note late in the wrong note error sequences, as reflected by longer IKIs on the post-error keystroke. These wrong note errors are more similar to traditional errors showing post-error slowing and a reduction of velocity on the error (for a review, see Danielmeier & Ullsperger, 2011; Debener et al., 2005; Rabbitt, 1966), in which an incorrect motor plan and command is carried out but without any corrective responses to compensate for the error.

Both error types show a different pattern than observed in previous piano performance experiments. In solo piano performance, pre- and post-error slowing affected all three keystrokes before and after the error (Ruiz et al., 2009). However, playing in synchrony is a different task to playing solo. In solo playing, a performer can adjust timing to help recover from an error. This adjustment is constrained when playing in synchrony, as the goal is to keep in time with a partner. In the current study, pianists were instructed to continue playing if an error was made by themselves or by their partner. Thus, when a player made an error, the partner kept the pace steady as the player responded to the error either by reducing speed for a wrong note error or by executing a quick correction for an extra note error. The errors of a partner did not affect a pianist's performance, as it was their task to keep playing so the partner could re-join after recovering from the error.

The error responses to the error types are slightly different, but both provide evidence to support the adaptive orienting theory (Wessel, 2018; Wessel & Aron, 2017). The theory posits that an unexpected event, such as an error, initiates a cascade of behavioural and neural responses, including global motor suppression, due to an event that resulted in outcomes different than predicted. With wrong note errors, post-error slowing was observed, but no corrective action was taken. This response can be explained through the idea of global motor suppression that follows an unexpected action outcome. Suppression is the first response to an error and is likely initiated through internal monitoring (Cooke & Diggles, 1984). An incorrect motor plan was developed and carried out. The lack of corrective action may suggest that a correct response motor plan was not developed in time to allow for corrective action following the error, given the timing demands of staying in synchrony with a partner. Leading up to the wrong note errors, participants showed a reduction in their keystroke velocity on keystrokes E-2 and E, as well as a non-significant reduction in velocity on keystroke E-1. A reduction in velocity means that the participants played the key with less force. This can suggest uncertainty about upcoming actions, as reduced velocity has been found in research on errors in piano performance (Maidhof et al., 2009; Ruiz et al., 2009) and errors in typing (Rabbitt, 1978).

It is possible that the reduction in velocity earlier in the wrong note error sequences (i.e., on keystroke E-2) resulted in a more explicit step-by-step monitoring (Baumeister, 1984; Masters, 1992) and reduced participants' level of playing, leading to a breakdown in performance. Highly skilled actions become automated, with most processes running outside of working memory (J. R. Anderson, 1993; Beilock & Carr, 2001; Fitts & Posner, 1967) and attention to the motor processes of these automated actions harms experienced performers (Beilock, Bertenthal, Hoerger, & Carr, 2008; Beilock, Bertenthal, McCoy, & Carr, 2004; Beilock, Carr, MacMahon, & Starkes, 2002; Yarrow, Brown, & Krakauer, 2009). Thus, a reduction in velocity may draw the performer's attention to the motor movements being carried out and make them more prone to commit an error. The interpretation of these results as a breakdown in performance is further supported by the asynchrony results which show a reduced level of synchrony between partners during wrong note error sequences.

Extra note errors were instances of a finger slipping from one note to a neighbouring note and were followed by quick corrective action by fitting two keystrokes into the space of an average correct keystroke. These quick keystrokes were also played with significantly reduced keystroke velocity. The finger slips may have resulted from response conflict (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick et al., 2004; Carter et al., 1998). Multiple internal models can be developed in parallel for highly trained actions (Haruno, Wolpert, & Kawato, 2001; Wolpert & Kawato, 1998). These multiple models may result in response conflict if the performer is unsure which response needs to be carried out next. The conflict then delays the response, the error response is carried out, but then corrected almost immediately, as the correct response had been developed in parallel with the error response.

Research has shown that error-correcting responses are faster than equivalent correct responses (Cooke & Diggles, 1984; Rabbitt, 1966, 2002). According to Cooke and Diggles (1984) and in line with the adaptive orienting theory (Wessel, 2018; Wessel & Aron, 2017), the first step in error correction is the suppression of the muscle providing the movement. This suppression occurs as early as 50 ms before any overt sign of the action; therefore the authors concluded the suppression is likely based on the internal monitoring of the motor commands (Cooke & Diggles, 1984). Further, research in typing suggests that attempts can be made to pull back an error, resulting in less velocity used in hitting the key (Rabbitt, 1978). The extra note errors in the current experiment were corrected quickly – performers still had time after the error to execute the correct action to regain synchrony with their partner and regain pitch accuracy. Thus the corrective processes were started before the error was committed. This allowed for suppression of the behavioural error response, as seen in the very short IKI and the reduced velocity. The correct response may be developed in parallel with the error response, just at a slightly slower pace, allowing the error response to be produced first (Gehring et al., 1993) and quickly corrected as the ongoing internal comparison realised a discrepancy between the estimated outcome and desired outcome. However, given the time course of these immediate corrections, with the actions being carried out less than 100 ms after error occurrence, it is unlikely these corrections result from intentional action but are automatic and unreflective responses (Rabbitt, Cumming, & Vyas, 1978; Ullsperger, Danielmeier, et al., 2014; Yeung & Summerfield, 2012). It is more likely that these error-correcting responses are actually delayed correct responses (Rabbitt, 2002). The internal models of these delayed correct responses may be initiated and developed in parallel with the error responses, allowing for the corrected response to be carried out immediately after an early error response (Rodríguez-Fornells et al., 2002; Ullsperger & von Cramon, 2006; Wolpert & Kawato, 1998; Yeung, Botvinick, & Cohen, 2004).

Another, possibly complementary, explanation is that extra note errors could be action slips that are instances of biomechanical implementation failure (Botvinick & Bylsma, 2005; Heckhausen & Beckmann, 1990; Reason, 1990). This idea would suggest the intention and planning before the action were correct, but the action failed at implementation. As extra note errors were quickly corrected, it seems reasonable to assume that the correct intentions and motor plans were prepared prior to the execution of the actions, but an incorrect action was subsequently implemented. A biomechanical implementation failure could occur within the framework of response conflict, so these explanations need not be mutually exclusive but may be interconnected. Future research may be able to disentangle errors involving response conflict and biomechanical implementation failures.

Thus, the adaptive orienting theory is supported by data from errors that result from an incorrect motor command, such as pressing an incorrect key in the current study, and also supported by data from errors that result from response conflict, and possible biomechanical implementation failure, followed by a quick correction. Both types of errors show a suppression of the error response, but a difference in adapting to the error after that suppression. In the case of wrong note errors, the suppression continued through to the next note, showing reduced speed on the post-error note. In the case of extra note errors, suppression of the error occurred earlier and corrective action was implemented within the time frame of an average correct keystroke, allowing for minimal disruption of synchrony between the two players.

This difference in responses to errors can be understood in a more general way. In certain situations where an incorrect motor command is carried out, such as doing the wrong dance steps or making an error during a musical performance, sometimes the error cannot be corrected, due to timing constraints or performance standards. For example, a wrong dance step or incorrect pitch may go unnoticed by the audience, but if you slow or stop to correct it, that may draw the audience's attention to the error or may cause more errors due to timing issues. Further, experienced performers demonstrate more anticipatory behaviour as opposed to perseveratory behaviour (Palmer & Drake, 1997), suggesting that performers would be more likely to focus on future and upcoming actions as opposed to past actions.

However, some error situations, such as missing a step while going down stairs, require immediate corrective action. An accidental error may need some reaction or quick correction to avoid or minimise consequences. For example, if the only response was slowing down after a missed step while going down stairs, there would be very little chance to recover or minimise injury. The slowing response would not allow for catching oneself or moving the feet fast enough to compensate for that missed step. However, quick reactive and corrective movements can help recover from the missed step and the additional consequence of falling down the stairs may be avoided. For well-practiced actions, it has been theorized that multiple parallel pairs of inverse and forward models are generated, with the most appropriate one selected given the context and environment (Haruno et al., 2001; Wolpert & Kawato, 1998). So when a step is missed, corrective movements that have been developed in parallel with the incorrect action are carried out to regain balance and prevent falling down more steps. Thus, while global motor suppression can explain initial slowing responses to unexpected error events, it does not account for the quick reactive and corrective motor movements with the aim of avoiding further consequences. These actions may be internally developed in parallel with incorrect movements so that if there are any unexpected events or errors, corrective actions can be implemented as the incorrect actions are being suppressed.

2.4.2 EEG Data

2.4.2.1 Self-produced Errors

Self-produced errors were expected to elicit either an ERN or a pre-ERN, both followed by a Pe, as shown in previous research on error processing (Gehring et al., 2012; Maidhof et al., 2009; Ruiz et al., 2009). Self-produced performance errors elicited the ERN component from 30 to 90 ms. Amplitude of the EEG component from 30 to 90 ms was more negative when performers played error notes compared to playing correct notes, specifically in the middle anterior region of interest. This is in line with previous research in error processing, as the ERN is thought to be generated in the anterior cingulate cortex (Gehring et al., 2012).The ERN was followed by the Pe peaking around 170 ms. Amplitude of the Pe was larger when performers played error notes compared to playing correct notes in all regions of interest except the right posterior.

The agency manipulation showed no significant results. This was contrary to the hypotheses, but indicates that highly trained musicians were able to distinguish their own performance from their partner's, even when that distinction was made more difficult. This was unexpected, but not surprising, as previous research has shown that experts are better at identifying their own actions than the actions of others (Knoblich & Flach, 2003; Loula et al., 2005; Repp & Knoblich, 2004) and have developed strong action-perception coupling through extensive training (Novembre & Keller, 2014; Zatorre et al., 2007). This may allow for increased self-other distinction even under ambiguous agency conditions. As the behavioural data revealed differences depending on error type, the EEG data were similarly split to investigate differences in neural activity depending on error type (extra note errors and wrong note errors). As with the results from the non-split data, extra note errors elicited the ERN peaking around 40 ms after error onset. The amplitude of the ERN was larger when playing extra note errors than when playing wrong note errors or correct notes, specifically in the middle anterior region of interest. As discussed in the section on behavioural data, the extra error notes were followed by a very quick correction. Thus, the results are consistent with previous research showing that corrected errors elicit larger ERN amplitudes compared to uncorrected errors (Fiehler, Ullsperger, & von Cramon, 2004, 2005; Gehring et al., 1993; Kalfaoğlu et al., 2018; Rodríguez-Fornells et al., 2002; Ullsperger, Danielmeier, et al., 2014), although there is also evidence that corrected errors elicit smaller ERN amplitudes compared to uncorrected errors (Ullsperger & von Cramon, 2006).

These results also partially support the conflict monitoring theory of error processing, suggesting that error responses result from pre-response conflict (Carter et al., 1998). The conflict monitoring theory posits that the ERN is elicited by conflict between multiple competing responses and that an error response reinforces the conflict, resulting in post-error slowing (Ullsperger, Danielmeier, et al., 2014). It is possible that, in the current experiment, the competing motor responses were developed in parallel internally, resulting in response conflict. The behavioural results show pre-error slowing, a result which has been explained as response inhibition that allows additional time for deciding between competing responses (Brittain et al., 2012; Frank, 2006). Further, the automatic correction suggests that the correct motor response was available, just delayed. There is evidence of a dissociation between error processing and conflict monitoring (Burle et al., 2008; Garavan et al., 2003; Iannaccone et al., 2015), however there may be interactions between these processes as some conflict-related processing functions seem to be reflected in the ERN (Iannaccone et al., 2015).

Wrong note errors elicited a pre-ERN peaking around 30 ms before error onset. Amplitude of the pre-ERN was greatest in the posterior regions of interest, especially on the right side. The latency of this component is comparable to the pre-ERN observed in previous piano studies on performance errors (Maidhof et al., 2009; Ruiz et al., 2009). As suggested with the behavioural data on wrong note errors, this could suggest a breakdown in performance leading to early processing of an error. In the Ruiz, et al. (2009) piano study that reported a pre-ERN, a reduction in velocity was observed in the keystrokes leading up to the error as well. Ruiz et al. (2009) and Maidhof et al. (2009) attributed the pre-ERN and velocity reduction to early error detection. However, the comparison between wrong note errors and extra note errors and the measures of asynchrony in the current experiment gives some additional insight to this interpretation. If a pre-ERN does indicate early error detection, that would suggest an increased chance to correct the error. Instead, the data showed that wrong note errors were left uncorrected and extra note errors were corrected. As noted above, error correction can occur within 30 ms of error commission. Given that the pre-ERN was observed approximately 50 ms pre-error, this could allow for corrective action to override the error before it is committed. Because of this, it seems unlikely that the pre-ERN is related to error detection, but may instead be an indicator of performance breakdown leading to an error.

Both the ERN and pre-ERN were followed by the Pe peaking around 170 ms. In the middle anterior region of interest, amplitude of the Pe was larger when playing extra note errors compared to playing correct notes. In the middle centre region of interest, amplitude of the Pe was larger when playing either extra note errors or wrong note errors compared to playing correct notes. Previous research has suggested that the Pe is related to error awareness (Godefroid et al., 2016; Hewig et al., 2011; Murphy et al., 2012; Nieuwenhuis et al., 2001). As the extra note errors were quickly corrected, it is reasonable to think that performers were aware of making these errors, at least aware enough to correct the errors. Performers were also likely aware of the errors during wrong note sequences. Although there were predictions that the effect of agency may be observed in differences in Pe amplitude, no significant differences were found related to agency.

It is interesting to note that the difference in latencies of the negative error-related components elicited by extra note errors and wrong note errors. Extra note errors elicited an ERN comparable to that in standard error processing. In contrast, wrong note errors elicited a pre-ERN, even though the wrong note errors followed the typical pre-error speeding and post-error slowing pattern behaviourally. As discussed in the section on behavioural data, extra note errors were corrected errors – an incorrect note was inserted into an otherwise correct sequence. The error note had a very short IKI and was followed by the correct note with a short IKI (although not as short as the error note), resulting in a quick error and quick recovery. Wrong note errors were uncorrected errors. In these cases, an incorrect note was played instead of a correct note. Prior to the error, there seemed to be a breakdown in performance as indexed by inconsistency in velocity and synchrony. After the error, performers demonstrated post-error slowing. Thus, during extra note errors, a correct motor plan was developed in parallel with the error motor plan and was implemented immediately after the error was committed. During wrong note errors, a correct motor plan may have been developed, but not in time for it to be carried out after the error.

2.4.2.2 Responses to Other-produced Errors

Errors of a partner were expected to elicit the FRN component followed by a P300. In the current study, errors of a partner elicited an FRN with a latency of 215 – 300 ms, peaking around 275 ms. Amplitude of the FRN was greater for error keystrokes than correct keystrokes in the left and middle centre regions of interest, as well as the left and middle posterior regions of interest. These results are consistent with results of previous research in joint action and error processing (Loehr et al., 2013; Nieuwenhuis, Holroyd, et al., 2004).

No P300 component was observed. This may be due to the speed at which participants were playing. As the P300 can be observed at a latency between 250 to 500 ms (Kühn et al., 2011; Loehr et al., 2013; Nieuwenhuis, Holroyd, et al., 2004), there may have been too much interference from other keystrokes to observe a P300 component. At an average IKI of 164 ms per keystroke, participants would already be two or more keystrokes beyond the error. As with the self-produced errors, other-produced errors did not show any effects of the agency manipulation.

2.4.3 General Conclusions

The current findings indicate that highly skilled performers can distinguish their own performance from a partner's even when agency is highly ambiguous. Participants demonstrated a high level of error awareness within their own and their partner's playing, regardless of whether agency was ambiguous. Highly skilled pianists spend years practising and monitoring their own playing. Thus, even when playing with a partner, performance monitoring levels are very high and ambiguity of agency does not affect their ability to monitor their own or their partner's performance. Expert performers have developed strong internal models through years of practice and training (Keller et al., 2016; Wolpert et al., 1995) that allow for strong monitoring and prediction of a partner's performance as well. Research has shown that people are sensitive to the subtle variations in timing of actions, allowing for them to distinguish their own performance from others' (Flach, Knoblich, & Prinz, 2003, 2004; Keller et al., 2007; Knoblich & Flach, 2001; Knoblich, Seigerschmidt, Flach, & Prinz, 2002). Further, previous performance of a specific action allows for the performer to better simulate and predict those action outcomes (Knoblich et al., 2002; Lahav et al., 2007). This also allows for increased prediction of those same actions being performed by another (Knoblich et al., 2002). Thus, in highly skilled performers, error awareness remains consistent even when it is more difficult to distinguish between their own performance and a partner's performance.

The lack of agency effect may also be in part due to reduced attention given to the pitch dimension. In the task, participants' main priority was staying in synchrony with their partners, emphasizing timing over pitch concerns. As timing is prioritized over pitch in synchronization tasks (Prince & Pfordresher, 2012), the agency manipulation in the pitch dimension would have been less attended to than activity in the timing dimension. This issue might be investigated in the future. Alternatively, lack of effects of the agency manipulation may indicate that expert pianists rely on proprioceptive and tactile feedback more than auditory feedback when monitoring their own performance (Finney, 1997; Maidhof et al., 2013; Maidhof et al., 2009; Repp, 1999; Ruiz et al., 2009; van der Steen, Molendijk, Altenmüller, & Furuya, 2014). If error processing is triggered by proprioceptive and tactile feedback, auditory feedback is redundant and the agency manipulation in pitch may not result in agency ambiguity.

Taken together, the behavioural and EEG results do not match predictions based on previous piano performance experiments with solo pianists (Maidhof et al., 2013; Maidhof et al., 2009; Ruiz et al., 2009), but are comparable to EEG results found in error processing for discrete tasks

(Gehring et al., 2012). Results from the current experiment may differ from previous piano performance studies because solo playing is internally self-paced, allowing the performer greater freedom to adjust their timing to recover from an error. By contrast, timing in duo performance is constrained by the need for co-performers to maintain synchrony, which creates a situation where each individual is to some degree externally paced by the other, leaving little room for one individual to delay while the other carries on. Error management strategies, which are a vital component of skilled performance (Kruse-Weber & Parncutt, 2014), may thus differ for solo and ensemble performance. Further, in previous studies, an isolated error only needed to be preceded and followed by three correct keystrokes, whereas in the current study, there was the additional criterion that the partner's concurrent performance needed to be error-free. Perhaps as a consequence of this, the current study had a slightly lower isolated error rate compared to previous studies (0.3% compared to 0.7% in Ruiz et al., 2009).

Further, the pre-ERN in the current study showed a different topography than previous studies. In Maidhof et al. (2009) and Ruiz et al. (2009), the pre-ERN was found in fronto-central regions, whereas in the current study, amplitude of the pre-ERN was greatest in the posterior ROIs, especially on the right side. Several differences between those studies and the current study may have influenced pre-ERN topography. In the current study, performers were instructed to visually monitor their hands while playing, whereas in previous studies, performers were prevented from visual monitoring of the hands. This was done to facilitate re-synchronization with the partner when an error was made. Furthermore, the current study used a joint action setting whereas the previous studies investigated solo performance.

The current findings demonstrate that different types of self-produced errors are processed at different latencies in expert performers. Uncorrected errors (i.e., wrong note errors) were processed before the error occurred and demonstrated pre-error reduction in velocity, post-error slowing, and reduced synchronization with the partner, whereas corrected errors (i.e., extra note errors) were processed after the error occurred and demonstrated error and post-error reduction in velocity, error and post-error speeding, and a higher level of synchronization with the partner (except on the error note itself). Highly trained musicians have an expert knowledge of their instrument and the movements involved in performing on their instrument. This expertise increases cortical areas involved in action planning and comprehension (Yang, 2015). These task-specific cortical changes allow experts to process errors efficiently and may allow for detection of errors from the initiation of an incorrect motor plan. In such cases, experts are able to process the error early and may engage strategies to correct the error or reduce the consequences of the error. Additional research is needed to determine how agency ambiguity affects performance in joint action, but the ambiguity needs to be in a dimension that is prioritized within the task.

Chapter 3

Experiment 2

3.1 Introduction

Perception and recognition of errors are important cognitive processes, allowing us to identify our own and others mistakes. Perception and recognition of errors by others occurs when observing the actions of others or when observing a recording of one's own or another's actions. During action errors, these performance monitoring processes can induce a global motor suppression (Wessel & Aron, 2017) and elicit specific event-related potential (ERP) components recorded from electroencephalographic (EEG) activity. During observation, performance monitoring processes elicit similar ERP components.

Observed and perceived errors elicit a feedback-related negativity (FRN) that peaks around 250 ms after error onset (Gehring et al., 2012; Miltner et al., 1997). The FRN is usually followed by the P300 component (Ullsperger, Fischer, et al., 2014). Self-produced errors usually elicit the error-related negativity (ERN; for a review, see Gehring et al., 2012), however when feedback is the only indication that an error has been committed, self-produced errors elicit the FRN instead of the ERN (Holroyd & Coles, 2002; Stahl, 2010). Theories explaining the FRN posit that it is elicited by a mismatch between the perceived and predicted outcomes (Holroyd & Coles, 2002; Nieuwenhuis, Holroyd, et al., 2004). The predicted outcomes are based on internal models of the motor plan (Wolpert et al., 1995; Wolpert & Kawato, 1998; Wolpert et al., 1998). Internal models consist of inverse and forward models, with the inverse model generating the motor plan to be carried out. An efference copy of the motor plan is used by the forward model to generate predictions about the outcome of the planned action. The predicted outcome is then compared to the actual outcome and if the outcomes do not match, a negative component is elicited. When feedback is the first indication that the predicted and actual outcomes do not match, the negative component elicited is the FRN, peaking approximately 250 ms after onset of the feedback (Holroyd & Coles, 2002; Stahl, 2010). Research shows that FRN amplitude is affected by the relation between the predicted outcome and the actual outcome – amplitude of the FRN was larger when the mismatch between expected and actual outcomes was larger (Nieuwenhuis, Holroyd, et al., 2004). Additionally, there is evidence that the FRN reflects reward prediction error (Chase et al., 2011; Fischer & Ullsperger, 2013; Holroyd & Coles, 2002; Holroyd & Krigolson, 2007; Rutledge et al., 2010; Talmi et al., 2012).

Observation of errors also occurs when people are acting together. Similar to committing an error oneself, the perception of errors of a co-acting partner results in behavioural post-error slowing in one's own actions (de Bruijn et al., 2012). This demonstrates that the actions of a partner affect one's own behaviour. When looking at neural activity, observing a partner's error elicits the FRN component, usually followed by the P300 (for a review, see Nieuwenhuis, Holroyd, et al., 2004). Research in music performance has investigated error processing as well, showing that errors in a partner's part elicit the FRN (see Results section from Chapter 2; Loehr, Kourtis, & Brazil, 2015; Loehr et al., 2013). Results from the previous experiment in this thesis showed that co-acting partner's errors elicited the FRN while pianists continued to monitor their own performance, but did not show any behavioural adaptation to the errors of their partner (see Section 2.3 and Section 2.4.3). Thus, even when acting alongside a partner, people are able to perceive and process the errors of others, resulting in error-related neural activity and often accompanied by behavioural changes.

Familiarity with a partner and their actions affects observation of performance. The most familiar actions are self-produced actions, as people have a lifetime of experience with their own actions. Evidence supports that people are better at identifying their own actions than the actions of others and better at recognising the actions of a friend than actions of a stranger (Loula et al., 2005). Further, pianists are better able to recognize their own performance (Repp & Knoblich, 2004), better able to synchronise with recordings of themselves than with recordings of others (Keller et al., 2007), and better able to synchronise with those who are closely matched in terms of solo performance timing (Loehr & Palmer, 2011). Pianists are also better at detecting manipulations of timing in their own performance than in another pianist's, but only when there were already self-other differences in timing (Repp & Keller, 2010). Familiarity with a partner's part also increases co-representation and simulation of their part (Loehr et al., 2013; Novembre et al., 2012, 2014; Ragert et al., 2013), allowing for better prediction of their action outcomes. Taken together, familiarity and experience can help with self-identification of previously performed actions. Additionally, familiarity and action experience with a partner, their action style, and their part may facilitate identification of the performer.

Self-other distinction is an important aspect of agency, enabling people to identify their own performance from the performance of others. Agency is the ability to control one's own actions, use them to control events in the environment, and recognise that those actions are self-produced (Haggard & Chambon, 2012; Haggard & Tsakiris, 2009). A sense of agency develops out of multiple cues including perceptual, sensorimotor, and cognitive cues (Knoblich & Repp, 2009; Pacherie, 2008, 2012; Sato, 2009; Weiss et al., 2014). The two distinct aspects of agency are the judgement of agency and the feeling of agency (for a review, see Haggard & Tsakiris, 2009). The judgement of agency is a higher-order, explicit, and reflective process, while the feeling of agency is a lower-level, sensorimotor process (David et al., 2008). The judgement of agency relies on belief states and inferences to attribute agency to an action (Aarts et al., 2005; Wegner, 2003). When assessing agency of previously performed actions, judgement of agency may rely more heavily on belief states, as inferences from contextual and environmental cues may be altered from the time of performance. Feeling of agency may contribute to assessing agency of previously performed actions through simulations of the actions.

In the previous experiment (see Chapter 2), pairs of pianists played short piano pieces together. The pieces were played at a quick pace in order to induce errors. Behavioural and neural responses to the self-produced and partner-produced error sequences and correct sequences were compared. Results showed that self-produced errors were processed differently depending on whether the error was corrected or left uncorrected, while errors of a partner elicited the FRN component but demonstrated no behavioural adjustments. For the current experiment, the pianists were invited to listen to short excerpts of their previous performance as it remains unclear how belief of agency for previously performed actions affects neural responses to perceived errors. The purpose of the current experiment was to investigate how belief of agency affects the neural indices of perception of own, a partner's, and an unfamiliar person's errors. To this end, pianists listened to short excerpts of recordings of themselves, their partner, and unfamiliar participants from the previous experiment. Participants were asked to indicate who performed the excerpt (self, partner, unfamiliar participant) and if there was a pitch error in the excerpt (yes or no). Belief of agency was measured with participants' responses to who performed the excerpt. Analyses were performed on response accuracy to the two questions and on EEG activity time-locked to the onset of the final note of the musical excerpt. Based on previous literature, it was expected that participants would be most accurate at identifying their own performance (Flach et al., 2003, 2004; Keller et al., 2007; Knoblich & Flach, 2003; Loula et al., 2005; Repp & Keller, 2010; Repp &

Knoblich, 2004) and also more accurate at identifying the performance of a partner (Loula et al., 2005) compared to an unfamiliar participant.

Research in typing has shown that belief of agency is enough to claim ownership of an error (Logan & Crump, 2010). In the study, participants typed while the researchers corrected some errors and inserted errors into some correct words. Participants were more likely to claim agency over corrections and take blame for inserted errors, accepting what was on the screen as opposed to what they actually typed. However, the post-error slowing results showed the opposite effect – participants slowed down after corrected errors but not after inserted errors. This suggests that the visual sensory feedback can override the declarative sense of agency over actions, but the actions are still processed in a way that is consistent with the actual agency. Thus, there may be a difference in behavioural responses and neural responses to perceived errors in the current experiment. Behavioural responses require a declarative response (i.e., a button press to indicate the performer of the excerpt) which would reflect the belief of agency but neural responses may reflect a different, implicit sense of agency that may not match the declarative sense of agency.

There were a few different hypotheses about the possible effects of belief of agency on the FRN and P300. There is evidence of a correlation between FRN amplitude and a sense of responsibility for the error (S. J. Anderson, 2014; Li, Han, Lei, Holroyd, & Li, 2011; Li et al., 2010). Using gambling tasks, these studies showed that there was an increase in FRN amplitude when participants felt a sense of responsibility over the error. Based on these previous results, the current study may show an increase in FRN amplitude when a participant believes the excerpt contained an error and that the error was performed by the self compared to believing the error was committed by another performer, regardless of whether the excerpt was actually a self error.

Alternatively, there may be some subconscious ownership of the error that could be based on the internal modelling process being calibrated to one's own action style (Keller et al., 2007; Keller et al., 2016). Extensive training and practice develops strong action-perception coupling in musicians (Novembre & Keller, 2014; Zatorre et al., 2007), allowing for increased ability to simulate and predict action outcomes that fall within their expertise. However, the increased ability may not extend to a declarative awareness of one's own performance just from perceiving it. This would result in greater FRN amplitudes for self-performed errors regardless of belief.

Another possibility is that perceptual experience is sufficient for the participant to take some ownership of the error, or that the timing information is enough to take ownership of the performance (Schütz-Bosbach & Prinz, 2007). If this is the case, amplitude of the FRN should only show a difference when the excerpts were performed by an unfamiliar performer. Pianists had perceptual and motor experience with their own performance, as they performed the music, visually monitored their fingers while playing, and heard the music while playing. They also had perceptual experience with their partner's performance, as they heard the music their partner was playing during the previous experiment. With an unfamiliar participant, pianists knew the music they were playing, but never heard or experienced the performance of any non-partner. Thus, if perceptual experience is sufficient to develop a belief of agency over the performance, that may be reflected in the neural responses to errors.

Finally, it is possible there will be some difference in neural activity prior to the error. Research suggests that highly trained musicians process music in an anticipatory way (Novembre & Keller, 2014; Palmer & Drake, 1997; Panasiti et al., 2016; Sammler et al., 2013). Further, the previous experiment and research investigating solo piano performance (Maidhof et al., 2013; Maidhof et al., 2009; Ruiz et al., 2009) provide evidence that some self-performed errors are processed before the completion of the error. Thus, if there are some cues in the performance leading up to an error, there may be some indication of this in the neural activity leading up to the error.

3.2 Methods

3.2.1 Participants

Participants were 17 highly skilled pianists who had completed the previous experiment (reported in Chapter 2). Participants had an age range of 19 – 75 years (*M* = 36.8 years, *SD* = 17.08 years, 13 female; see Figure 3.1 for age distribution). All participants reported normal hearing and gave informed consent to participate in the study. On average, the participants had 12.2 years of piano training (*SD* = 5.19 years, range = 3 – 25 years). The experiment was approved by the local ethics committee and all participants gave written informed consent for the experiment.

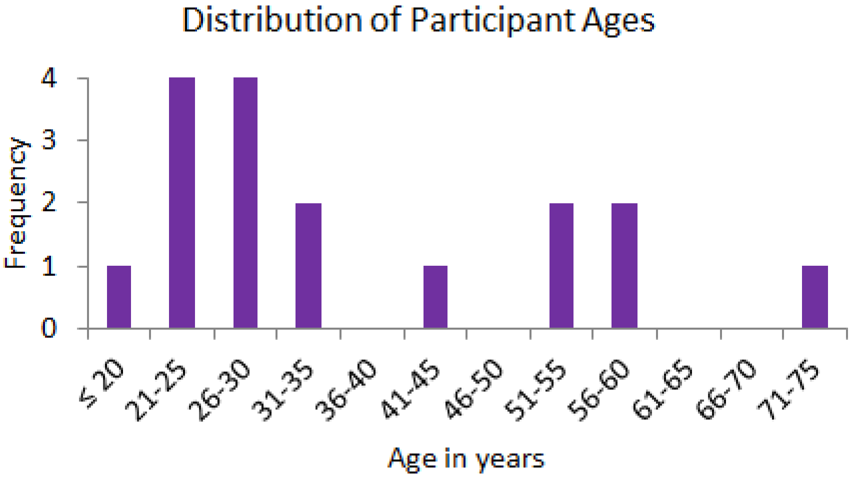


Figure 3.1. Distribution of participant ages. Participants' ages ranged from 19 to 75 years, with the majority of participants under the age of 35 years.

3.2.2 Materials

Stimuli were excerpts taken from recordings of the piano playing from the previous experiment completed over a year before. In the previous experiment, participants played memorised piano pieces (modified version of piano exercises by Charles-Louis Hanon; Hanon, 1923) in pairs. Participants played the pieces either on the same pitch (i.e., in unison) or one octave apart and participants focussed on maintaining synchrony with their partners. Participants continued playing if they or their partner made an error. Performances were recorded separately for each participant, and although participants were in separate booths, they heard each other's performances through headphones. For the current experiment, 11-note excerpts were taken from these recordings.

The excerpts were cut to three seconds in duration using MidiEditor software (www.midieditor.org), imported into MuseScore (musescore.org) to create .wav files, and then imported to Adobe Audition (Adobe, Inc.) to add a 10 ms fade-in and fade-out to each excerpt to eliminate any possible clicks at the beginning or end of the excerpt. Excerpts were set to this length of timing in order to keep the experiment length to two hours, to have a sufficient number of trials for statistical power to detect smaller ERP effects (Boudewyn, Luck, Farrens, & Kappenman, 2018), and to have an equal number of trials for each condition. Excerpts were given a two-second leading part with the expectation that participants would be able to recognize the piece from which the excerpt was taken and thus may be able to recognize errors in the excerpts.

Timing of each stimulus was adjusted so that the onset of the last note of the excerpt was set to two seconds after the start of the stimulus. This adjustment maintained the original timing, including the duration of all notes, but shifted the whole stimulus so that the onset of the last note started at the two-second mark. This timing shift was done so the EEG recording could be time-locked to the onset of that note in the excerpt. MIDI velocity of the second to last and last notes in the excerpts was adjusted to 70 if below the threshold of 40, to prevent an obvious difference between MIDI velocities from second last to last note of the stimulus. The threshold was set to 40 because the median velocity during correct keystrokes from the previous experiment was 70 with a standard deviation of 12. Anything over or under two-and-a-half times the standard deviation (i.e., over 100 or under 40) would be outside of the expected range of velocity for a keystroke.

Half of the excerpts contained a pitch error and half contained no pitch errors. For stimuli that contained a pitch error, the error was always the last note of the excerpt. Thus, stimuli selection was constrained to error sequences that had ten consecutive correct notes preceding the error and correct sequences that had eleven consecutive correct notes. In the previous experiment, a distinction was made between extra note errors and wrong note errors during analysis of the data. Only extra note errors were used in the stimuli for the current experiment because there were some participants who did not commit any wrong note errors with ten consecutive correct notes preceding the error.

For the current experiment, participants listened to excerpts performed by themselves, their partner, and unfamiliar pianists (i.e., participants they did not perform with during the previous experiment). Stimuli for the unfamiliar pianist condition came from a variety of participants in the previous experiment (including other participants that did the current experiment), thus the unfamiliar pianist stimuli was different for each participant. There was a standard set for the unfamiliar pianist condition, but some of the stimuli were changed out depending on who the participant was. For example, participant 301 could have stimuli from 801 and 802 for the unfamiliar pianist condition and then when participant 802 was tested, stimuli made from 301 and 302 could be in the unfamiliar pianist condition.

Presentation software (Neurobehavioral Systems, Inc.) controlled stimulus presentation and recorded the responses. Participants listened to the excerpts through EEG-compatible insert earphones (Etymotic Research, ER1). Questions were visually presented on a 24-inch BENQ monitor and participants responded to the questions on a standard computer keyboard.

3.2.3 Design and Procedure

Each participant listened to excerpts of piano playing recorded from the previous experiment. Participants listened to the excerpt presented through EEG-compatible earphones and then responded via computer keyboard to two forced-choice questions that were presented on the computer monitor. The stimulus presentation timeline is shown in Figure 3.2. The final note (either error or non-error) was always heard at 2000 ms (two seconds) after excerpt onset. The first question was presented 3000 ms (three seconds) after the start of the excerpt and asked who played the excerpt – self, partner, or unfamiliar participant. Participants responded by pressing labelled keys on the number line on a standard computer keyboard with their left hand (1 for self, 2 for partner, 3 for unfamiliar). The second question was presented immediately after the participant responded to the first question and asked if there was an error in the excerpt. Participants responded by pressing labelled keys on the number line on a standard computer keyboard with their right hand (9 for yes, 0 for no). Response and timing of response for each question was recorded.

The average trial length was 6.18 seconds (*SD* = 1.92 seconds). Continuous EEG activity was recorded throughout the experiment.

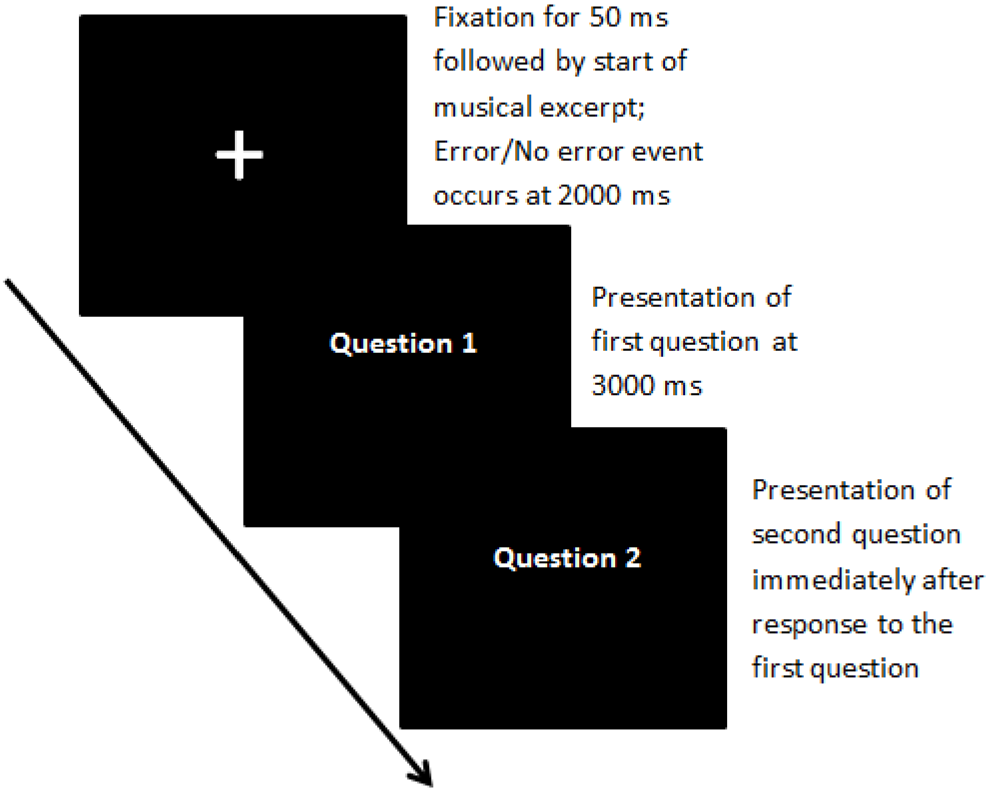


Figure 3.2. Schematic of experimental trial. Question 1 asked participants who performed the musical excerpt they heard. Question 2 asked if participants thought there was an error in the excerpt.

The excerpts participants listened to were from recordings that had been performed by the participant, their partner, or an unfamiliar participant from the previous experiment. Excerpts contained either one or no pitch errors. If there was a pitch error, it was the final pitch of the excerpt. Additionally, the stimuli were balanced by agency condition from the previous experiment. That is, in the previous experiment, agency ambiguity was manipulated by participants playing the piano pieces with the exact same pitch (ambiguous agency) or one octave apart (unambiguous agency).

Therefore, in this experiment, each participant listened to an equal number of excerpts that had been ambiguous and unambiguous. As participants were only listening to a single player's performance for each trial, the agency condition would not be noticeable, but this was controlled in case there were any differences in performance related to agency (such as more precise timing). Finally, in the previous experiment, errors were identified as wrong note errors and extra note errors. The stimuli for this experiment only included extra note errors because some participants had very few isolated wrong note errors.

Each participant completed 360 trials of which there were 60 trials in each condition (self error, self correct, partner error, partner correct, unfamiliar participant error, and unfamiliar participant correct) with 10 unique excerpts per condition. The 60 unique excerpts were presented six times each. The set of unique stimuli was shuffled before each of the six repetitions. Participants had a break after completing 120 trials and another break after completing 240 trials. After the experimental trials, participants answered a few questions about their background, the experiment, and their partner from the previous experiment (see questionnaire in Appendix C).

3.2.4 EEG Data Acquisition and Analyses

Continuous EEG signals were recorded from 64 Ag/AgCl electrodes placed over the scalp according to the extended 10-20 system (FPZ, FP1, FP2, AFZ, AF3, AF4, AF7, AF8, FZ, F1, F2, F3, F4, F5, F6, F7, F8, FCZ, FC1, FC2, FC3, FC4, FC5, FC6, FT7, FT8, CZ, C1, C2, C3, C4, C5, C6, T7, T8, CPZ, CP1, CP2,

CP3, CP4, CP5, CP6, TP7, TP8, PZ, P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, POZ, PO3, PO4, PO7, PO8, OZ, O1, O2, IZ), referenced to linked mastoids (M1, M2). The signals were amplified with a 24-bit BioSemi Active Two system (BioSemi B. V., Amsterdam, Netherlands). Vertical electrooculograms were recorded from the outer canthus of each eye and horizontal electrooculograms were recorded from above and below the right eye for each participant. Data were sampled at 512 Hz. Letswave 6 (www.letswave.org) was used for pre-processing and visualising the data. A band-pass filter (minimum – 0.5 Hz, maximum – 30 Hz) was applied to the data to remove linear trends, slow drifts, and power line noise. The data were visually inspected and trials containing technical and muscle artefacts (e.g., jaw movement) were removed. The data were cleaned of eye blinks and horizontal eye movements using independent component analysis (ICA). EEG data were epoched from -500 ms to 1 s, time-locked to the onset of the final note of the excerpt, and baseline corrected from 150 to 50 ms pre-onset of the final note, to have a baseline of 100 ms (S. J. Luck, 2014) and investigate differences between conditions just before the onset of the final note. Data from one participant was removed due to excessive noise in the EEG signal throughout the experiment leaving data from a total of 16 participants in the analysis.

Statistical analyses were conducted on the mean amplitudes in each condition for specific time windows for stimuli and responses with electrodes pooled into nine regions of interest (ROIs), split by laterality and anterior/posterior location. The ROIs were delineated as follows: left anterior – F3, F5, F7, FC3, FC5, FT7; left centre – C3, C5, T7, CP3, CP5, TP7; left posterior –

P3, P5, P7, PO3, PO7; middle anterior – F1, Fz, F2, FC1, FCz, FC2; middle centre – C1, Cz, C2, CP1, CPz, CP2; middle posterior – P1, Pz, P2, POz; right anterior – F4, F6, F8, FC4, FC6, FT8; right centre – C4, C6, T8, CP4, CP6, TP8; and right posterior – P4, P6, P8, PO4, PO8 (Sammler et al., 2013).

Analyses were carried out on ERP components to investigate neural responses to the actual performer (self, partner, unfamiliar participant). Additional analyses were carried out on ERP components to investigate neural responses to belief of performer. To conduct these analyses, ERP amplitudes for each category of response (self, partner, unfamiliar participant) were averaged separately across trials within each Performer condition. Thus, there were different numbers of responses that went into the average for each participant.

The time windows selected for analyses were 145 to 210 ms for the N1 and 210 to 290 ms for the P2. These time windows and classifications were based on visual inspection of the data and previous research (Näätänen & Picton, 1987; Paulmann, Bleichner, & Kotz, 2013; Pratt, 2012; Woods, 1995). Although the time windows may be considered late for these components, they would also be early for the N2/P3 components. Further, there are no components earlier in the data that could be the N1 or P2. These components are not related to the offset of the stimuli, as a short fade-in and fade-out was applied to the stimuli. Finally, the stimuli were converted from MIDI files, which can have a delay up to 20 ms between the MIDI onset and the sound.

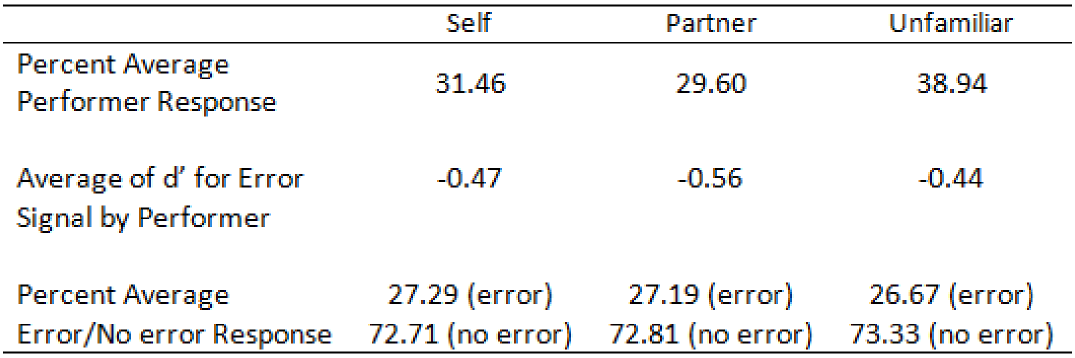
3.3 Results

3.3.1 Behavioural Results

Participants gave two behavioural responses, indicating who performed the excerpt and if there was an error in the excerpt. Responses to the performer question were evenly distributed (see Table 3.1) with no significant differences in response rate between self, partner, and unfamiliar performer ($F(2, 30) = 2.28$, $p = 0.12$). All response rates were not significantly different from chance level (all $p > 0.09$). Responses to the error question were biased toward responding that there was no error in the excerpt ($t(15) = 7.19$, $p < 0.001$; see Table 3.1). Analysis on overall response accuracy showed no significant effects (see Figure 3.3). Because of the response bias in the error/no error question, results were converted into d-prime scores. Analysis with d-prime scores also showed no significant results ($F(2, 30) = 0.26$, $p = 0.770$).

Table 3.1

Response rate for questions about performer and error detection



	Self	Partner	Unfamiliar
Percent Average Performer Response	31.46	29.60	38.94
Average of d' for Error Signal by Performer	-0.47	-0.56	-0.44
Percent Average Error/No error Response	27.29 (error) 72.71 (no error)	27.19 (error) 72.81 (no error)	26.67 (error) 73.33 (no error)

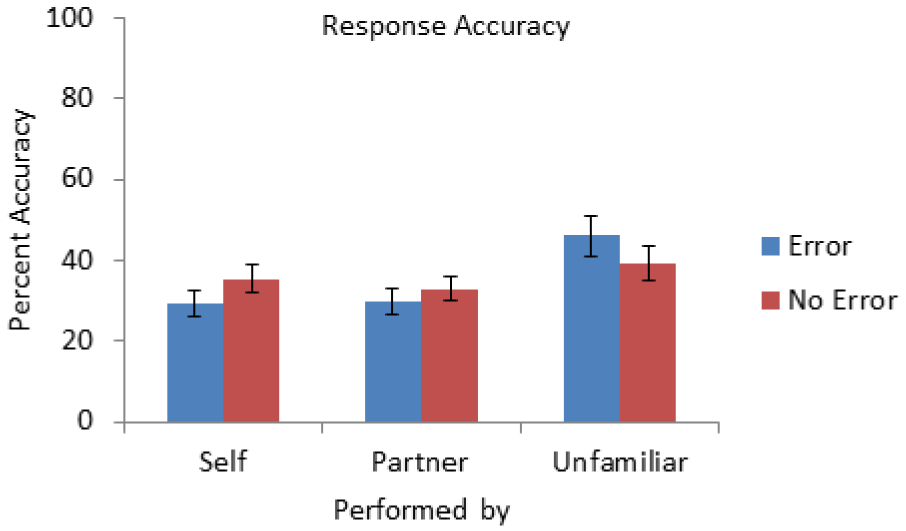


Figure 3.3. Average percent accuracy for when excerpt was performed by self, partner, or an unfamiliar participant and when the excerpt did (error) or did not (no error) contain a pitch error. Errors bar show standard error of the mean.

Responses from the questionnaire (see Table 3.2) show that most participants felt confident they recognized errors, although their responses during the experiment indicate they were biased to responding that there was no error in the excerpt. Responses to the recognition of excerpt performer were more consistent with the behavioural results of the experiment.

Table 3.2

Responses to the questions about partner familiarity, experience with partner and performance during the experiment

Familiarity with partner	Familiar	Unfamiliar	
	7	10	
More erroneous partner in previous experiment	Me	Partner	Unsure
	8	8	1
Able to recognize own performance	Yes	No	Maybe/Sometimes
	5	6	6
Able to distinguish between partner and unfamiliar player	Yes	No	Maybe/Sometimes
	7	8	2
Noticed errors	Yes	No	Maybe/Sometimes
	9	2	6

3.3.2 EEG Results

Based on previous literature on observed errors, it was predicted that a pitch error in the stimuli would elicit an FRN possibly followed by a P300, or possibly some error-related neural activity leading up to the error. However, the data showed the N1/P2 complex, with amplitude of the N1 peaking around 185 ms and amplitude of the P2 peaking around 260 ms (see Figures 3.4 and 3.6, respectively). A 3 x 3 x 3 x 2 (Lateralisation [left/middle/right] x Anterior/Posterior [anterior/centre/posterior] x Performer [self/partner/unfamiliar] x Error/No Error) ANOVA was conducted on the N1 at the time window of 145 – 210 ms. Results showed a significant main effect of Lateralisation ($F(1.56, 23.34) = 8.40$, $p = 0.003$), a significant main effect of Anterior/Posterior ($F(1.15, 17.20) = 5.82$, $p = 0.024$), and a marginally significant main effect of Performer ($F(1.78, 26.66) = 3.40$, $p = 0.053$; see Table 3.3 for full

ANOVA results). Amplitude of the N1 was significantly larger in the middle regions of interest than the left ($t(15) = 4.66$, $p < 0.001$) or right ($t(15) = 2.74$, $p = 0.015$) regions of interest regardless of Performer or Error/No error (see Figure 3.5). Amplitude of the N1 was significantly larger in the anterior than in the posterior regions of interest ($t(15) = 2.47$, $p = 0.026$) and significantly larger in the centre than in the posterior regions of interest ($t(15) = 3.45$, $p = 0.004$; see Figure 3.5) regardless of Lateralization, Performer, or Error/No error. Amplitude of the N1 was significantly larger when the excerpt had been performed by an unfamiliar participant than when performed by the self ($t(15) = 2.29$, $p = 0.037$; see Figure 3.5) regardless of Lateralization, Anterior/Posterior location, or Error/No error. There were no other main effects or any significant interactions.

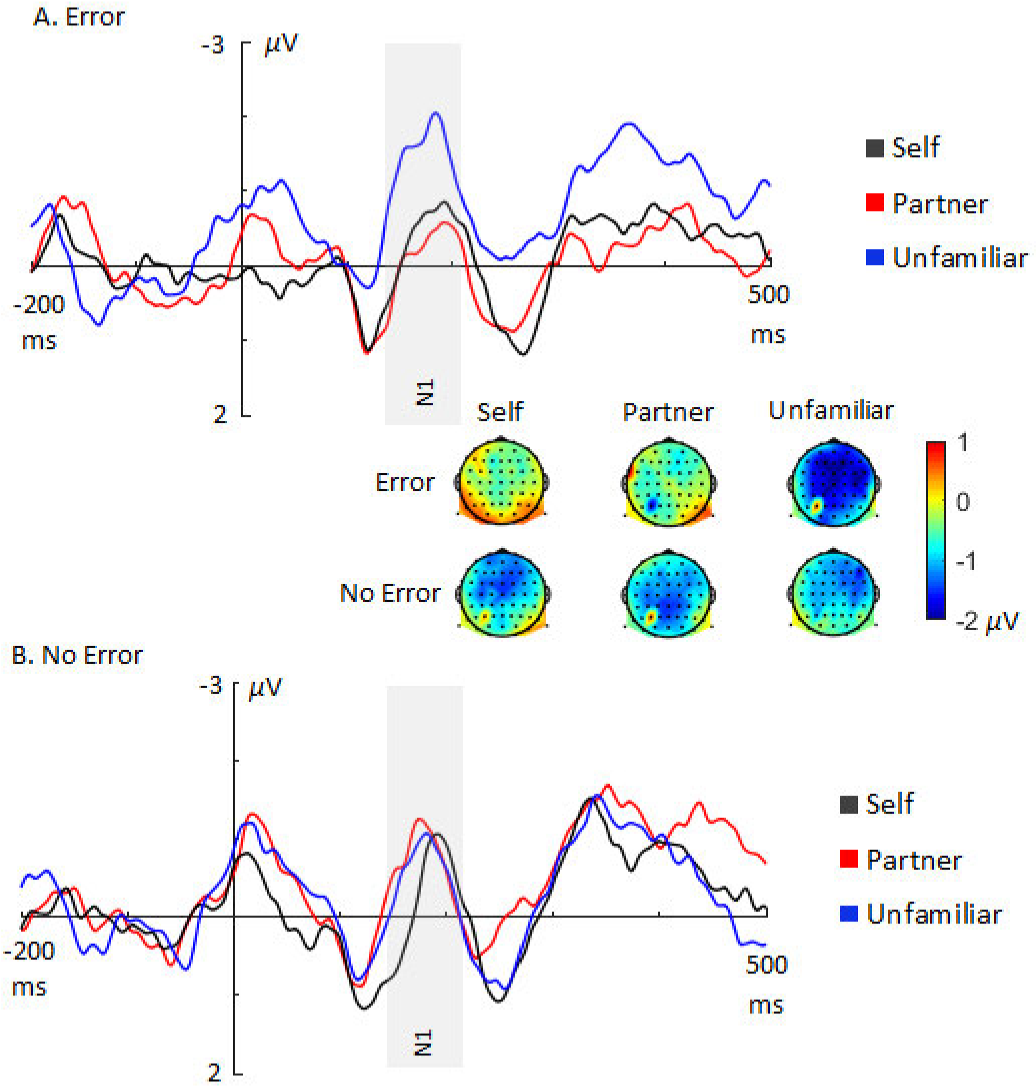


Figure 3.4. Grand-averaged waveforms showing the N1 (145 – 210 ms, shaded) during listening time-locked to onset of final pitch of excerpts performed by self (black), partner (red), and an unfamiliar participant (blue) with (A.) and without (dashed.) a pitch error as the final note. Waves are from electrode F1. Scalp voltage distributions for each condition are shown at 185 ms.

Table 3.3

ANOVA values for analysis of N1 during perception of excerpts with or without an error at a time window of 145 – 210 ms with factors of Lateralization x Anterior/Posterior x Performer x Error/No error.

Effect	*df*	*F*	*p*-value	η_p^2
L/R	**(1.56, 23.34)**	**8.40**	**0.003**	**0.359**
A/P	**(1.15, 17.20)**	**5.82**	**0.024**	**0.28**
Performer	(1.78, 26.66)	3.40	0.053	0.185
E/NE	(1, 15)	0.04	0.838	0.003
L/R x A/P	(1.70, 25.56)	3.30	0.06	0.18
L/R x Performer	(1.94, 29.13)	1.19	0.318	0.073
A/P x Performer	(1.82, 27.27)	0.46	0.615	0.03
L/R x A/P x Performer	(2.94, 44.09)	0.84	0.478	0.053
L/R x E/NE	(1.76, 26.39)	0.23	0.768	0.015
A/P x E/NE	(1.18, 17.73)	0.01	0.943	0.001
L/R x A/P x E/NE	(1.90, 28.55)	0.13	0.871	0.008
Performer x E/NE	(2, 29.97)	0.90	0.417	0.057
L/R x Performer x E/NE	(2.88, 43.23)	0.76	0.517	0.048
A/P x Performer x E/NE	(1.97, 29.58)	0.79	0.46	0.05
L/R x A/P x Performer x E/NE	(3.03, 45.38)	0.84	0.48	0.053

Note: Bold values indicate significant results ($p < 0.05$). L/R = Left/Middle/Right; A/P = Anterior/Centre/Posterior; Performer = self/partner/unfamiliar; E/NE = Error/No error.

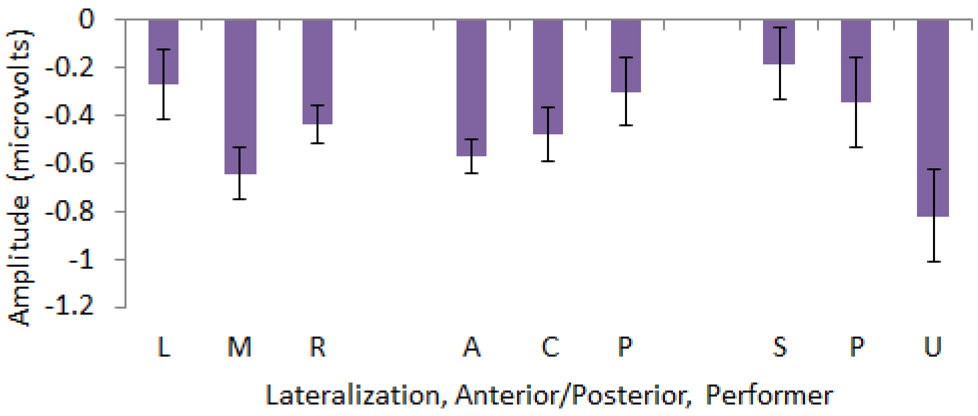


Figure 3.5 Amplitude (in microvolts) of N1 time-locked to final note of excerpt, showing main effects of Lateralisation (Left, Middle, Right), Anterior/Posterior (Anterior, Centre, Posterior), and Performer (Self, Partner, Unfamiliar).

The P2 was observed from 210 – 290 ms (see Figure 3.6) and was analysed with a 3 x 3 x 3 x 2 (Lateralisation [left/middle/right] x Anterior/Posterior [anterior/centre/posterior] x Performer [self/partner/unfamiliar] x Error/No error) ANOVA. Results showed a significant main effect of Lateralisation ($F(1.79, 26.80) = 4.99$, $p = 0.017$) and a significant interaction of Lateralisation and Anterior/Posterior ($F(1.54, 23.10) = 4.13$, $p = 0.038$; see Table 3.4 for full ANOVA results). Further analysis of the interaction showed that amplitude of the P2 was significantly larger in the left anterior than the right anterior region of interest ($t(15) = 2.33$, $p = 0.034$) and also significantly larger in the middle anterior than the right anterior region of interest ($t(15) = 3.07$, $p = 0.008$). In the centre regions of interest, amplitude of the P2 was significantly larger in the middle centre compared to the right centre region of interest ($t(15) = 3.17$, $p = 0.006$; see Figure 3.7). There were no other main effects or interactions.

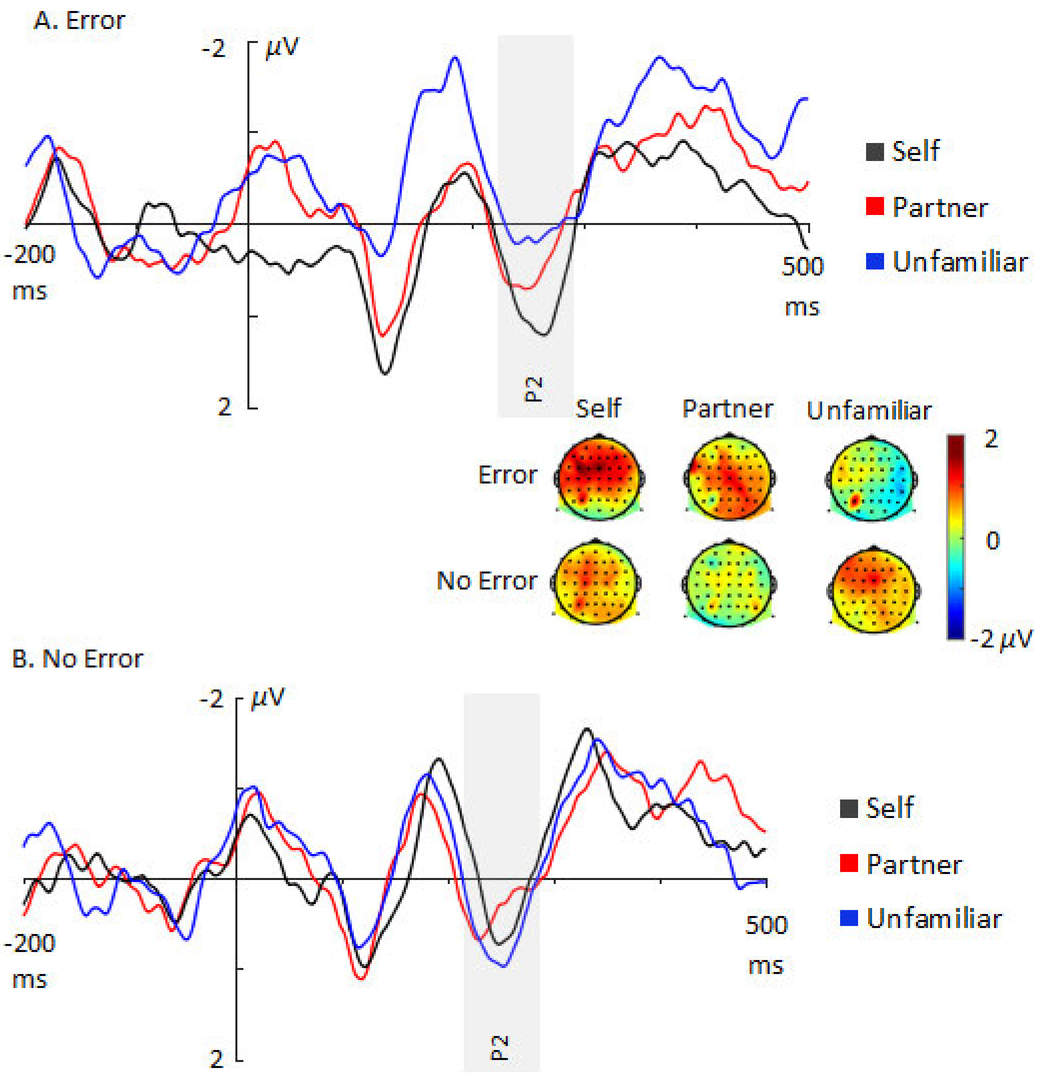


Figure 3.6 Grand-averaged waveforms showing the P2 (210 – 290 ms, shaded) during listening time-locked to onset of final pitch of excerpts performed by self (black), partner (red), and an unfamiliar participant (blue) with (A.) and without (dashed.) a pitch error as the final note. Waves are from electrode Fz. Scalp voltage distributions for each condition are shown at 260 ms.

Table 3.4

ANOVA values for analysis of P2 during perception of excerpts with or without an error at a time window of 210 – 290 ms with factors of Lateralization x Anterior/Posterior x Performer x Error/No error.

Effect	*df*	*F*	*p*-value	η_p^2
L/R	**(1.79, 26.80)**	**4.99**	**0.017**	**0.25**
A/P	(1.16, 17.36)	0.23	0.669	0.015
Performer	(1.89, 28.37)	1.11	0.339	0.069
E/NE	(1, 15)	0.10	0.754	0.007
L/R x A/P	**(1.54, 23.10)**	**4.13**	**0.038**	**0.216**
L/R x Performer	(2.42, 36.24)	0.63	0.567	0.04
A/P x Performer	(1.71, 25.62)	0.30	0.709	0.02
L/R x A/P x Performer	(3.13, 46.94)	0.72	0.554	0.045
L/R x E/NE	(1.58, 23.71)	0.10	0.858	0.007
A/P x E/NE	(1.42, 21.30)	0.99	0.361	0.062
L/R x A/P x E/NE	(1.52, 22.73)	1.08	0.341	0.067
Performer x E/NE	(1.95, 29.22)	0.34	0.712	0.022
L/R x Performer x E/NE	(2.42, 36.25)	0.54	0.619	0.035
A/P x Performer x E/NE	(2.41, 36.10)	1.25	0.304	0.077
L/R x A/P x Performer x E/NE	(2.79, 41.84)	1.25	0.303	0.077

Note: Bold values indicate significant results ($p < 0.05$). L/R = Left/Middle/Right; A/P = Anterior/Centre/Posterior; Performer = self/partner/unfamiliar; E/NE = Error/No error.

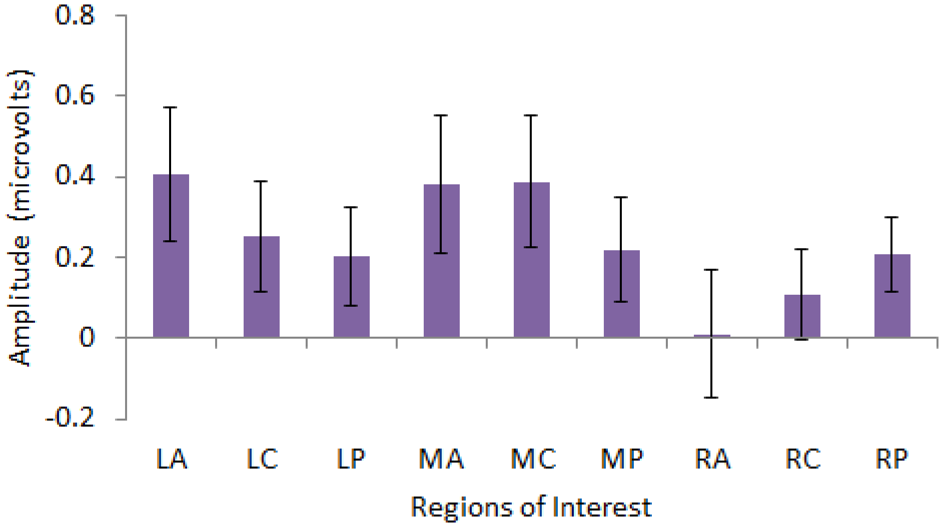


Figure 3.7 Amplitude (in microvolts) of P2 time-locked to final note of excerpt, showing the interaction between Lateralisation (L = Left, M = Middle, R = Right) and Anterior/Posterior (A = Anterior, C = Centre, P = Posterior).

To investigate EEG activity related to belief of agency, further analyses were carried out including participants' responses to the question about who performed the excerpt. For the N1 (see Figure 3.8), a 3 x 3 x 3 x 3 ANOVA (Lateralisation [left/middle/right] x Anterior/Posterior [anterior/centre/posterior] x Performer [self/partner/unfamiliar] x Response [self/partner/unfamiliar]) was conducted on the time window of 145 – 210 ms. Full ANOVA results are shown in Table 3.5. This analysis yielded a significant main effect of Lateralisation ($F(1.25, 18.78) = 5.63$, $p = 0.023$) and a significant main effect of Performer ($F(1.63, 24.40) = 4.26$, $p = 0.033$). Amplitude of the N1 was significantly more negative in the middle regions of interest than in the left ($t(15) = 3.35$, $p = 0.004$) or right regions of interest ($t(15) = 3.23$, $p = 0.006$; see Figure 3.9A). Additionally, amplitude of the N1 was significantly more negative when the excerpt had been played by an unfamiliar participant than when played by the self ($t(15) = 3.07$, $p = 0.008$) or by the partner ($t(15) = 2.19$, $p = 0.045$; see Figure 3.9B).

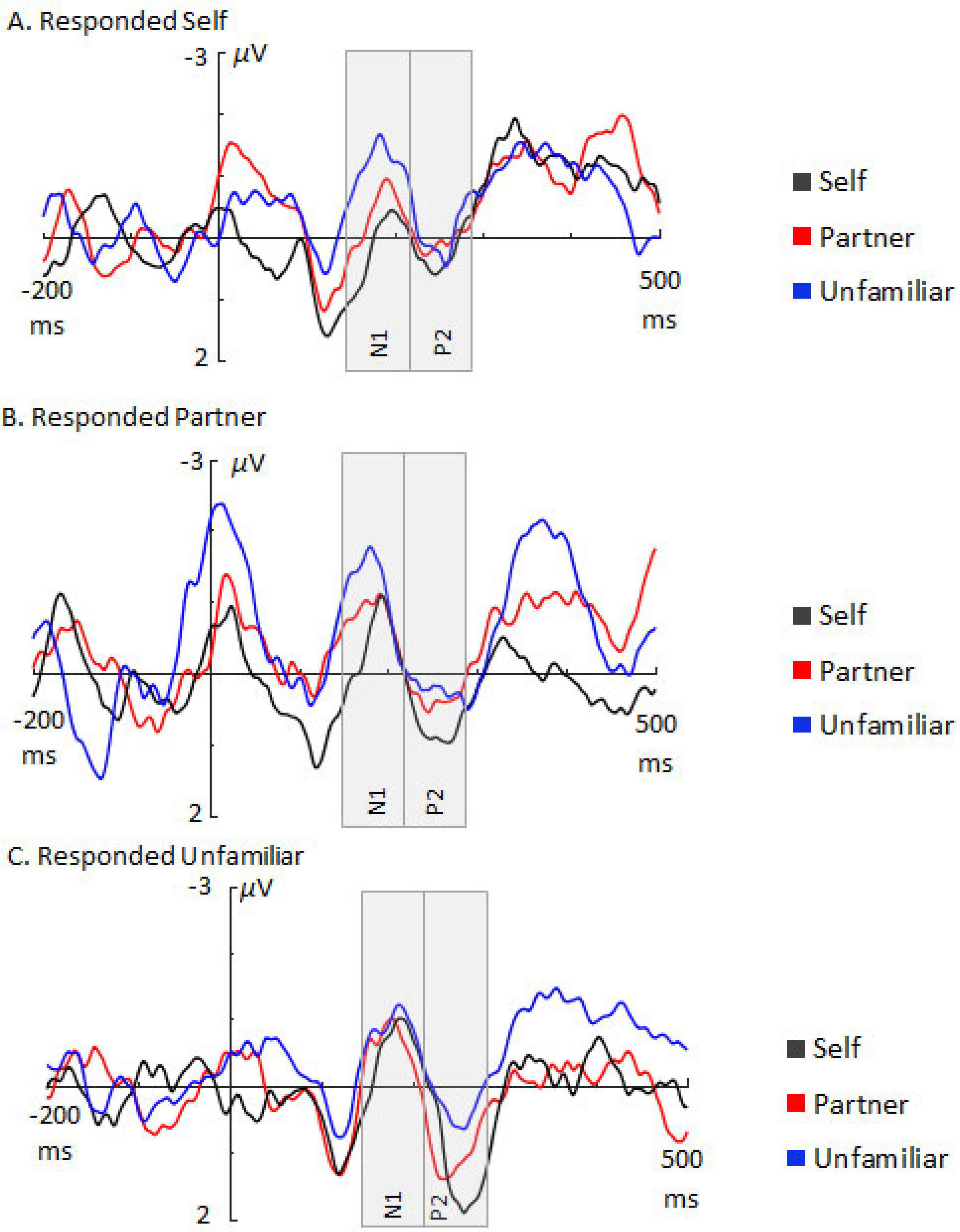


Figure 3.8. Grand-averaged waveforms showing the N1 (145 - 210 ms) and the P2 (210 – 290 ms) during listening time-locked to onset of final pitch of excerpts performed by self (black), partner (red), and an unfamiliar participant (blue) when participant responded self (A.), partner (B.), and unfamiliar participant (C.). Waves are from electrode F1.

Table 3.5

ANOVA values for analysis of N1 during a time window of 145 – 210 ms for response to excerpts performed by self, partner, and an unfamiliar performer with factors of Lateralization x Anterior/Posterior x Performer x Response.

Effect	*df*	*F*	*p*-value	η_p^2
L/R	**(1.25, 18.78)**	**5.63**	**0.023**	**0.273**
A/P	(1.13, 17.01)	0.91	0.368	0.057
Performer	**(1.63, 24.40)**	**4.26**	**0.033**	**0.221**
Response	(1.86, 27.97)	2.02	0.154	0.119
L/R x A/P	(1.59, 23.82)	1.25	0.297	0.077
L/R x Performer	(3.60, 53.99)	0.68	0.593	0.043
A/P x Performer	(1.89, 28.39)	0.15	0.849	0.01
L/R x A/P x Performer	(3.53, 52.90)	0.77	0.536	0.049
L/R x Response	(3.31, 49.63)	0.91	0.449	0.057
A/P x Response	(2.04, 30.60)	0.59	0.564	0.038
L/R x A/P x Response	(3.60, 54.07)	0.90	0.464	0.056
Performer x Response	(2.08, 31.21)	0.11	0.901	0.007
L/R x Performer x Response	(4.53, 67.98)	0.80	0.541	0.051
A/P x Performer x Response	(3.69, 55.36)	0.63	0.629	0.04
L/R x A/P x Performer x Response	(5.97, 89.48)	0.98	0.443	0.061

Note: Bold values indicate significant results ($p < 0.05$). L/R = Left/Middle/Right; A/P = Anterior/Centre/Posterior; Performer = self/partner/unfamiliar; Response = self/partner/unfamiliar.

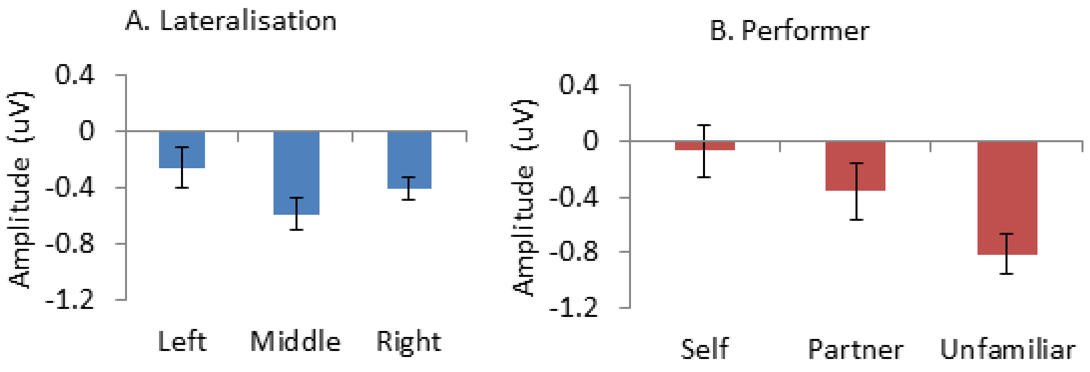


Figure 3.9. Amplitude (in microvolts) of N1, during the time window of 145-210 ms after the final note of the excerpt, showing the main effects of A. Lateralisation (Left, Middle, Right) and B. Performer (Self, Partner, Unfamiliar).

The corresponding analysis was performed on the P2 for the time window of 210 – 290 ms (see Figure 3.8). The 3 x 3 x 3 x 3 (Lateralisation [left/middle/right] x Anterior/Posterior [anterior/centre/posterior] x Performer [self/partner/unfamiliar] x Response [self/partner/unfamiliar]) ANOVA yielded a marginally significant main effect of Lateralisation ($F(1.62, 24.34) = 3.42$, $p = 0.058$), a significant main effect of Response ($F(1.67, 25.04) = 5.71$, $p = 0.012$), and a significant interaction of Lateralisation and Anterior/Posterior ($F(1.60, 24) = 3.89$, $p = 0.043$). Full ANOVA results are shown in Table 3.6. Further analysis showed that the amplitude of the P2 was significantly larger when participants responded that the excerpt was performed by an unfamiliar participant than when they responded that the excerpt was performed by the self ($t(15) = 4.47$, $p < 0.001$; see Figure 3.10). As in the earlier analysis of the P2, the interaction revealed that the amplitude of the P2 was significantly larger in the middle anterior region of interest than the right anterior region of interest ($t(15) = 3.35$, $p = 0.004$) and also significantly larger in the middle centre region of interest than in the right centre region of interest ($t(15) = 3.02$, $p = 0.009$; see Figure 3.11).

Table 3.6

ANOVA values for analysis of P2 during a time window of 210 – 245 ms for response to excerpts performed by self, partner, and an unfamiliar performer with factors of Lateralization x Anterior/Posterior x Performer x Response.

Effect	*df*	*F*	*p*-value	η_p^2
L/R	(1.62, 24.34)	3.42	0.058	0.185
A/P	(1.13, 16.88)	0.42	0.548	0.027
Performer	(1.46, 21.87)	2.12	0.154	0.124
Response	**(1.67, 25.04)**	**5.71**	**0.012**	**0.276**
L/R x A/P	**(1.60, 24.00)**	**3.89**	**0.043**	**0.206**
L/R x Performer	(2.62, 39.33)	0.62	0.585	0.04
A/P x Performer	(2.09, 31.34)	0.49	0.624	0.032
L/R x A/P x Performer	(4.10, 61.43)	1.19	0.326	0.073
L/R x Response	(3.53, 53.00)	0.63	0.623	0.04
A/P x Response	(1.86, 27.91)	1.37	0.27	0.084
L/R x A/P x Response	(4.32, 64.82)	0.95	0.446	0.06
Performer x Response	(3.43, 51.41)	1.27	0.296	0.078
L/R x Performer x Response	(4.33, 64.93)	0.64	0.648	0.041
A/P x Performer x Response	(3.70, 55.44)	1.66	0.177	0.10
L/R x A/P x Performer x Response	(5.33, 79.94)	0.65	0.671	0.042

Note: Bold values indicate significant results ($p < 0.05$). L/R = Left/Middle/Right; A/P = Anterior/Centre/Posterior; Performer = self/partner/unfamiliar; Response = self/partner/unfamiliar.

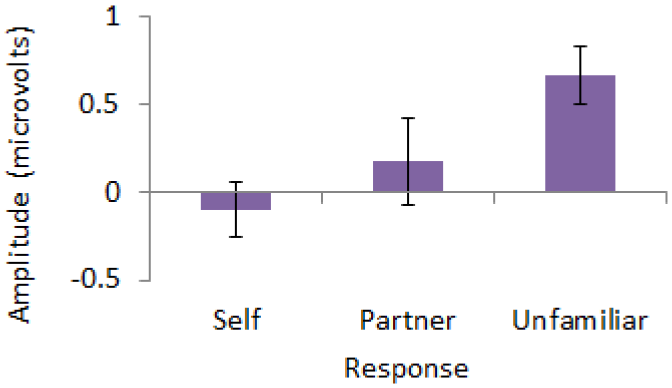


Figure 3.10 Amplitude (in microvolts) of P2 time-locked to final note of excerpt, showing the main effect of Response (Self, Partner, Unfamiliar).

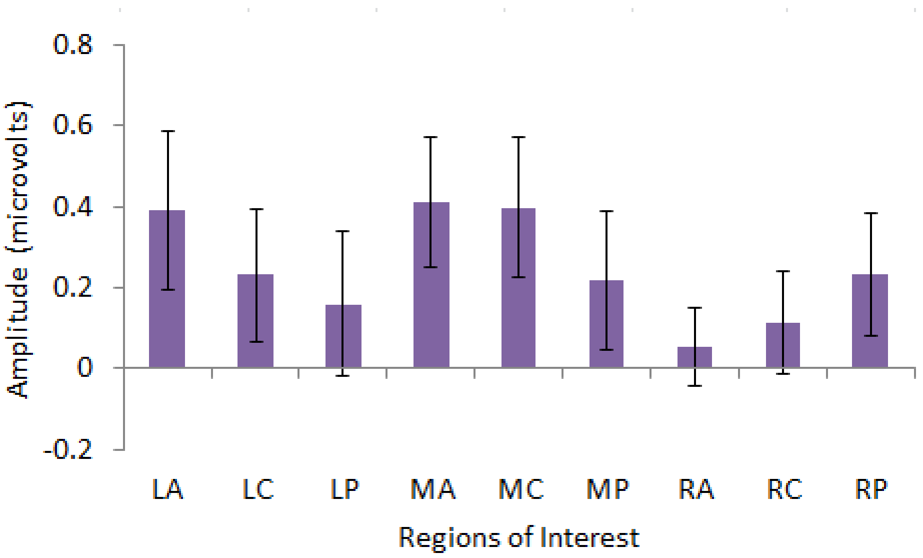


Figure 3.11. Amplitude (in microvolts) of P2 time-locked to final note of excerpt, showing the interaction between Lateralisation (L = Left, M = Middle, R = Right) and Anterior/Posterior (A = Anterior, C = Centre, P = Posterior).

3.4 Discussion

The aim of this experiment was to investigate the effect of belief of agency on the neural responses to perceived errors. Participants listened to short excerpts of a previous performance played by themselves, their previous partners, and unfamiliar participants from a previous experiment in which they performed technically challenging pieces in piano duos. Participants indicated who they thought performed the excerpt and if the excerpt contained an error.

3.4.1 Behavioural Data

Although it was expected that participants might be able to identify their own performance, and that of their previous partners, participants were at chance levels with their responses when trying to identify the performer.

This is in contrast to previous research involving self recognition of previously performed actions (Flach et al., 2003, 2004; Knoblich & Flach, 2003; Loula et al., 2005) and, more relevantly, in piano performance (Keller et al., 2007; Repp & Knoblich, 2004). These results may be due to the length of the excerpts. Excerpts were only two seconds long. This was because of timing constraints within the experiment and the number of conditions that needed to be included to analyse the EEG data. There is evidence that just a 500 ms excerpt of music can elicit a feeling of familiarity (Filipic, Tillmann, & Bigand, 2010). However, that feeling of familiarity may not be enough for participants to declaratively identify the performer.

Another possibility is that the previous studies involving recognition of piano performance used music that included expressive timing (Keller et al., 2007; Repp & Knoblich, 2004). That would allow for idiosyncratic stylistic preferences and timings in the performance that performers may pick up on. In the current experiment, excerpts were taken from a previous experiment in which participants played together in pairs. Research has shown that performers reduce variability in their actions in order to increase interpersonal coordination (Vesper, van der Wel, Knoblich, & Sebanz, 2011). Thus, in order to maintain synchrony, it was important for both players to keep steady timing and reduce variation within their own performance, making it easier for the partner to predict their actions. However, this may have reduced the microtiming variations and expressive timing that allow performers to identify their own previous performance. Future work looking at belief of agency within music performance should use longer excerpts so participants may be better able to identify who performed the excerpt. Alternatively, having participants listen to both parts together may help in identifying performance, but would not have been possible in this experiment, as participants played the exact same notes during some trials. These options would allow for an investigation of accuracy for belief of agency and how that accuracy may affect neural responses to the performance.

It was also predicted that participants might be able to identify errors in the excerpts, as they had a high familiarity with the pieces from which the excerpts were taken. However, participants were biased in reporting that there was no pitch error in the excerpt. The majority of responses (average of 64.5 percent overall) indicated no pitch error whereas chance level would have been 50 percent. This may also be due to the length of the excerpts. Participants may not have been able to recognise which piece was being played in the excerpt, as the excerpt could have started at any point in the recording. For example, most excerpts started somewhere in the middle of a piece, and not at the start of a musical phrase or bar. Starting the excerpt at the beginning of a bar would have been a useful cue in helping participants recognise the piece and identify errors. However, the choice of excerpt was constrained by the errors that were performed in the previous experiment. As such, there were very few errors in the previous experiment that would have met the criteria if the excerpt needed to start at the beginning of a bar, and not enough to make stimuli for the current experiment. Further, pitch errors in piano performance usually fit within the harmonic or diatonic context of the music (Palmer & van de Sande, 1993; Sloboda, 1974). This makes pitch errors difficult to detect, even for expert pianists (Repp, 1996). Pitch errors used in the current experiment did fit within the diatonic context, thus it may have been difficult for participants to detect the pitch errors throughout the experiment. Thus, error recognition may have been better if the excerpts were longer and provided more context for the listeners, but not necessarily, as it is difficult to detect diatonically-appropriate piano errors.

3.4.2 EEG Data

The EEG data provided a different story from what was predicted as well. Because participants could not identify errors in the excerpts and were biased to responding that the excerpts did not contain an error, the predictions for the EEG data were not met. It was expected that the EEG data would reveal an FRN possibly followed by a P300 for either excerpts that contained an error or excerpts that participants thought contained an error. Instead, the data showed the N1/P2 complex, regardless of whether there was an error or if participants thought there was an error. The amplitude of the N1/P2 complex seemed to be modulated by familiarity. The N1 is an auditory evoked potential with a latency usually between 60 and 160 ms after onset of a sound (for a review, see Woods, 1995), although earlier research suggests a longer latency window, between 50 and 200 ms (Näätänen & Picton, 1987). It is thought to reflect the initial processing of an auditory stimulus (Näätänen & Picton, 1987). The N1 can be influenced by attention and arousal (for a review, see Feng et al., 2014; S. J. Luck, 2014) and when referring the auditory stimuli, this arousal may increase sensory and motor responses to sound (Novembre et al., 2018; Pratt, 2012). The N1 can also be modulated by unexpectedness or surprise (Batterink & Neville, 2013; Carrus, Pearce, & Bhattacharya, 2013; Koelsch & Jentschke, 2010; Novembre et al., 2018; Robinson, Breakspear, Young, & Johnston, 2019).

Interestingly, the EEG data for the current experiment revealed a main effect of performer during the N1 component. The amplitude of the N1 was greatest when the excerpt had been performed by an unfamiliar participant, compared to the self and the partner. Research shows that when something has been perceived previously but the context or circumstances under which it was perceived cannot be remembered, there may be an increase in cognitive resources in an attempt of identification (Morris, Cleary, & Still, 2008). This increase in cognitive resources is related to increases in autonomic arousal (Dawson, Filion, & Schell, 1989). Thus, it is possible that, in the current experiment, the excerpt of the unfamiliar participant may induce the most arousal due to a different level of familiarity compared to the performances by the self and by the partner. Participants would have previous motor and perceptual familiarity with their own performance and a perceptual familiarity with performance by their partner, as they had heard their partner's playing during the previous experiment. Familiarity with the performance of the unfamiliar participant would strictly be about the piano pieces, as all participants performed the same six pieces. Thus, as the N1 component is affected by arousal, this may explain the increased N1 amplitude for the performance by the unfamiliar participant.

Alternatively, the increased N1 amplitude for the unfamiliar performer could be related to unexpectedness or surprise. Previous research demonstrates that the N1 component is modulated by expectancy (Batterink & Neville, 2013; Carrus et al., 2013; Koelsch & Jentschke, 2010; Novembre et al., 2018; Robinson et al., 2019). As the performances of the unfamiliar participant were the least familiar of the excerpts, it is possible that performance was more unexpected or surprising than the performances that had been self-produced or partner-produced. Participants had motor and perceptual experience with their own past performance, as well as perceptual experience with their partner's past performance, but only basic knowledge (i.e., knowledge of the musical pieces) of an unfamiliar participant's performance. This could suggest that participants' previous perceptual experience (or perceptual resonance; for a review, see Schütz-Bosbach & Prinz, 2007) with the performances was sufficient for it to be processed similarly to the self-produced excerpts, as opposed to the less familiar, and therefore, more unexpected performance by an unfamiliar participant.

Sensory attenuation could play a role in both of these explanations. Sensory attenuation is the reduction of the perceived intensity of stimuli (action outcomes) when they were produced by the self, as opposed to externally produced (Blakemore et al., 1998). Sensory attenuation is classically associated with self-produced actions (Blakemore et al., 1999; Blakemore et al., 2000; Gentsch & Schütz-Bosbach, 2011; Kühn et al., 2011), however there is evidence that sensory attenuation can occur both during one's own performance of an action and during observation of another performing the same action (Sato, 2008). Further, during joint actions, sensory attenuation is especially likely to occur when there is no delay between one's own action and the expected outcome (Loehr, 2013). When there was a delay between own and partner's actions, causing a delay in the expected outcome, there was reduced sensory attenuation. During my previous experiment for this research project, the pianists were expected to play in synchrony, allowing for the possibility of sensory attenuation for both one's own and the partner's performance. Sensory attenuation could influence the memory of those performed and perceived actions, resulting in those memories being more familiar and the actions less unexpected than performances by unfamiliar participants. Consequently, less cognitive resources might have been required to process familiar performances compared to the unfamiliar performances.

The P2 is an auditory evoked potential that follows the N1, usually peaking between 160 and 250 ms after onset of an auditory stimulus (S. J. Luck, 2014; Paulmann et al., 2013; Pratt, 2012). Similarly to the N1, amplitude of the P2 is influenced by arousal (S. J. Luck, 2014; Paulmann et al., 2013). The results of analysis on the P2 showed a main effect of response – amplitude of the P2 was larger when people thought the excerpt was performed by an unfamiliar participant than by the self. Interestingly, P2 amplitudes for response (i.e., belief of agency) showed the same pattern (although the opposite direction, and without a significant difference with for partner) as the N1 amplitudes showed for actual performer. Research with visual stimuli has shown that the amplitude of the P2 decreased with increased familiarity (Caharel et al., 2002). It is possible that participants had a decreased feeling of familiarity for certain excerpts, leading to a response that those excerpts were performed by an unfamiliar participant.

Taken together, the EEG results may suggest that a decreased feeling of familiarity arising from an unfamiliar stimulus may be processed as unexpected or surprising, as reflected through an increase in N1 amplitude, whereas a decreased feeling of familiarity arising from the categorisation of a stimulus as unfamiliar may increase arousal and be reflected by an increase in P2 amplitude. As these effects were not expected, these conclusions are of a more speculative nature and further investigation of these ideas would be an interesting avenue for future work.

3.4.3 General Conclusions

In summary, this experiment provided unexpected results. The task was too difficult and participant responses were at chance level when trying to identify the performer and biased when trying to detect an error. The excerpts used in this experiment were too short to enable participants to identify the performer or recognise errors within the performance. Familiarity with one's own and a partner's playing style was not sufficient to identify the performer with two seconds of auditory information. However, the EEG data provides some interesting results. The N1 component showed increased amplitude when the excerpt had been performed by an unfamiliar participant, which may suggest that perceptual experience of previous performance (i.e., self-produced and partner-produced performance) was enough for the excerpt to be processed as more expected or unsurprising. The P2 component showed increased amplitude when the participant thought the excerpt was performed by an unfamiliar participant, which may suggest that the categorization of an excerpt as produced by someone unfamiliar increases arousal. Future work should focus on further exploring these possible effects.

Chapter 4

General Discussion and Conclusions

The aim of this research project was to investigate the role of agency in joint action and how agency may be considered within the framework of joint action models and theories of error processing. To this end, two EEG experiments were conducted with expert musicians – an experiment with a piano duo task with an agency manipulation and an experiment with a perceptual task of listening and responding to excerpts from the piano duo experiment. In this final chapter, I will briefly summarise the findings from each experiment and then discuss the overall findings within the context of the literature.

4.1 Summary of Experiment 1

In the first experiment, highly skilled pianists played piano pieces in pairs while performance and EEG activity were recorded. This experiment was designed so that errors within joint action could be investigated during an ecological task, as the errors were spontaneous and occurred naturally. An agency manipulation was included to investigate how agency ambiguity might affect error processing. Errors are often preceded by speeding and followed by slowing, reflecting a speed-accuracy trade-off (Wickelgren, 1977). However, this behavioural pattern seems to be specific to speeded reaction time tasks. In sequential tasks, such as piano playing and typing, research has shown pre-error and post-error slowing (Kalfaoğlu & Stafford, 2014; Maidhof et al., 2009; Ruiz et al., 2009). An adaptive theory of global motor suppression has been put forward to explain post-error slowing within a more general framework of unexpected events (Wessel, 2018; Wessel & Aron, 2017). This theory posits that any unexpected event results in a global motor suppression. Action errors are considered unexpected events as the expected outcome was not achieved.

Initial analyses of the data from this experiment revealed that the agency manipulation was not effective, but also showed a different pattern of results than previous studies conducted with solo pianists. The behavioural data showed a significant increase in speed on the error and post-error notes, with speed returning to normal (i.e., not different from speed of correctly played notes) after the post-error note. Further analyses revealed that these results could be explained by the error type, as different results were observed for wrong note errors and extra note errors. The increase in speed observed on the error and post-error notes was driven by extra note errors.

Wrong note errors showed the typical pattern of pre-error speeding and post-error slowing, along with inconsistent keystroke velocity and reduced synchrony with the partner. Wrong note errors presumably occurred because an incorrect motor plan and command was carried out with no correction. Additionally, wrong note errors show more inconsistency in performance before the error, as indicated by the inconsistent velocity and reduced synchrony pre-error. This may suggest a breakdown in performance leading up to the error, as regularity (i.e., consistency) increases accuracy and confidence in performance (Stevenson & Carlson, 2018).

Extra note errors showed a pattern of pre-error slowing, error note speeding, and post-error speeding, with reduced pre-error and error velocity. These differences can be attributed to the mechanics of the extra note errors. Extra note errors were instances in which a finger slipped from a one note onto another, usually neighbouring, note. This can happen quite readily when playing at a fast pace, as was required during the experiment – errors of inserting a neighbouring note are more likely to occur at a faster pace (Palmer & Pfordresher, 2003). Alternatively, the finger slip could be a result of response conflict. Research shows that response conflict can lead to response inhibition, allowing for additional time to decide on the appropriate response (Brittain et al., 2012; Frank, 2006). Thus, as the pre-error keystroke demonstrated reduced speed and velocity, a finger slip could reflect a lack of confidence in the correct response. Once the finger landed on the incorrect note, the participant quickly corrected the error.

The extra note occurred with such quick pace that it did not disrupt the timing of the performance. That is, during extra note errors, participants played two notes (one error, one correct) in place of one average correct note and kept in time with their partner. Thus, for extra note errors, a slightly delayed correct motor plan was developed in parallel with the incorrect motor plan (Haruno et al., 2001; Rabbitt, 2002; Wolpert & Kawato, 1998) and when the error was committed, it was followed by a quick correction.

The EEG data showed no effect of the agency manipulation, but also showed a different pattern of results than expected. Previous research in errors during piano performance showed a pre-ERN followed by a Pe (Maidhof et al., 2009; Ruiz et al., 2009). Initial analysis of the EEG data was conducted on the data pooled across error type and a subsequent analysis was conducted on the data split by error type (summarised below). The analysis on the pooled data revealed the ERN component, peaking around 70 ms post-error onset and located in the fronto-central regions of the brain. This was followed by the Pe component, which peaked around 170 ms and was broadly distributed across the cortex. Although these results are not consistent with the previous piano studies, they are comparable to standard EEG studies looking at error processing. EEG studies investigating error processing show a fronto-central ERN around 50 to 100 ms after error onset, followed by a Pe between 200 to 500 ms (Gehring et al., 2012).

As with the behavioural data, the EEG data was split by error type to determine if there were differences in neural activity due to error type. Extra note errors showed the same pattern as the overall data, consistent with previous literature in error processing. An ERN followed the error onset by approximately 40 ms and this was followed by the Pe. However, wrong note errors demonstrated the pattern found in the previous piano studies (Maidhof et al., 2009; Ruiz et al., 2009). A pre-ERN was elicited approximately 30 ms before the error onset and was followed by the Pe.

These results suggest that error type affects the latency at which the error is processed. Errors resulting from an incorrect motor plan with no corrective action (i.e., wrong note errors) were processed 30 ms before the error had been committed. These errors seem to indicate a breakdown in performance (Kalfaoğlu & Stafford, 2014; Palmer, Mathias, & Anderson, 2012), as keystrokes leading up to wrong note errors were played with less consistent velocity, reduced synchrony with the partner, and increased speed. This variability across pre-error performance measures may draw the performers' attention to the specific motor processes required to produce the keystrokes, causing a shift from automaticity to explicit step-by-step monitoring (J. R. Anderson, 1993; Baumeister, 1984; Beilock & Carr, 2001; Fitts & Posner, 1967; Masters, 1992). Attention to the motor processes of automated actions can result in degradation in performance for experienced performers (Beilock et al., 2008; Beilock et al., 2004; Beilock et al., 2002; Yarrow et al., 2009). Thus, the pre-ERN observed may reflect the degradation of performance, allowing for processing of the less-than-ideal performance before the error has been committed. By the time the error is committed, the degraded performance has already been processed.

Although wrong note errors were processed before error onset, errors resulting from an incorrect motor plan with a delayed correct response and followed by a correction (i.e., extra note errors) were processed 50 ms after the error was committed. Extra note errors demonstrated pre-error slowing and reduction in velocity, which may indicate response conflict, as stated earlier. If the correction is a delayed correct response, it is facilitated by the development of the correct response in parallel with the incorrect response (Rabbitt, 2002; Rabbitt et al., 1978; Rodríguez-Fornells et al., 2002; Ullsperger, Danielmeier, et al., 2014; Yeung & Summerfield, 2012). Thus, response conflict arises, inhibiting and slowing the pre-error response to allow time to make a decision (Brittain et al., 2012; Frank, 2006). The incorrect response was carried out but then automatically corrected, as the correct response was already prepared along with the incorrect response. These results support the conflict monitoring theory of error processing (Botvinick et al., 2004; Carter et al., 1998). Errors arising from these situations are then processed after error commission.

Extra note errors may be the result of biomechanical implementation failure (Botvinick & Bylsma, 2005; Heckhausen & Beckmann, 1990; Reason, 1990), which could occur within the framework of response conflict. In other words, the intention and planning leading up to the action were correct, but failed at action implementation. Extra note errors were incorrect actions, but were corrected quickly, suggesting that the correct intentions and motor plans were prepared prior to action execution, as is similarly suggested in the conflict monitoring theory. Future research may be able to distinguish the differences between errors involving response conflict and biomechanical implementation failures or provide evidence to unify these ideas under a more comprehensive theory.

Because this experiment involved joint action, response to errors of a partner could also be investigated. As expected, errors of a partner elicited the

FRN component, which peaked around 275 ms. The FRN is usually followed by the P300 component (in a dual piano task - Loehr et al., 2013; also, for a review, see Nieuwenhuis, Holroyd, et al., 2004), however no P300 was elicited following partner errors in this experiment. This can be explained by the sequential nature of the task and the speed at which performers were playing. After making or perceiving an error, participants kept playing and having to process the incoming notes. Thus, a later component such as the P300 would experience overlap and interference from processing the incoming notes. As in the self-produced data, no effects of agency were observed in the partner-produced data.

4.2 Summary of Experiment 2

In the second experiment, highly skilled pianists who completed the first experiment returned over a year later to listen to recordings from the first experiment. They listened to short excerpts performed by themselves, their partners, and unfamiliar participants, indicated who they thought performed the excerpt, and indicated if there was an error in the excerpt. It was expected that participants would be able to identify their own previous performance (Flach et al., 2003, 2004; Keller et al., 2007; Knoblich & Flach, 2003; Loula et al., 2005; Repp & Knoblich, 2004). However, participants could not accurately identify who performed the excerpt and were biased to responding that the excerpts were free of errors. This could be due to the shortness of the excerpts (excerpts were only three seconds long) or may be due to the lack of expressive timing in the excerpts (which were based on technical piano exercises), as previous studies demonstrating self recognition in piano performance used longer excerpts of expressive musical pieces (Keller et al., 2007; Repp & Knoblich, 2004).

The hypotheses for this experiment were contingent on the participants being able to detect errors within the excerpts. It was expected that the EEG data would show the FRN component, perhaps followed by the P300. However, because participants were unable to reliably detect errors, no FRN was observed. The EEG data showed the N1/P2 complex, with the N1 peaking around 185 ms and the P2 peaking around 260 ms. Excerpts performed by an unfamiliar participant elicited the N1 with the largest amplitude. One possible explanation for this result is that the excerpt of the unfamiliar participant may elicit the most arousal because of a lower level of familiarity in comparison to the excerpts by the self and by the partner. Familiarity may be based on individual micro-timing embedded in one's individual motor signature and if co-acting partners have similar motor signatures, they coordinate better than those who have different motor signatures (Słowiński et al., 2016). Similar motor signatures may increase a sense of familiarity with the performance of another person. When perceiving something familiar under contexts or circumstances that cannot be remembered, cognitive resources may increase in an attempt to identify it (Morris et al., 2008) and this increase in cognitive resources is related to increases in autonomic arousal (Dawson et al., 1989). Hearing the excerpt by the unfamiliar participant may induce the most arousal due to the lowest level of familiarity compared to excerpts by the self and the partner.

Another interpretation of the N1 results is related to expectancy, as N1 amplitude has been found to increase with unexpected stimuli in a range of contexts (Batterink & Neville, 2013; Carrus et al., 2013; Koelsch & Jentschke, 2010; Novembre et al., 2018; Robinson et al., 2019). Participants had motor and perceptual experience with their own previous performance and perceptual experience with their partner's previous performance, but for an unfamiliar participant, only knew the musical pieces being performed. Thus, performances by the unfamiliar participant were the least familiar, which may mean these excerpts were more unexpected than those produced by the self or by the partner. This may suggest that the perceptual experience (or perceptual resonance; for a review, see Schütz-Bosbach & Prinz, 2007) with the partner-produced performances was sufficient for those performances to be processed similarly to the self-produced excerpts.

Amplitude of the P2 component varied based on participant responses to who performed the excerpt. When participants thought the excerpt was performed by an unfamiliar participant, amplitude of the P2 was larger than when they thought it was performed by the self. There is evidence that amplitude of the P2 is negatively correlated with familiarity (i.e., an increase in familiarity corresponds to a decrease in amplitude; Caharel et al., 2002). Thus, participants may have experienced a decreased feeling of familiarity for certain excerpts, leading to the response that those excerpts were performed by an unfamiliar participant and a decrease in P2 amplitude.

4.3 Limitations

At the outset of this research project, a main aim was to investigate the role of agency – the ability to control one's own actions, to recognise the self as the producer of those actions, and to use those actions to affect events in the environment (Haggard & Chambon, 2012; Haggard & Tsakiris, 2009) – within a joint action context. In the research presented here, the first experiment manipulated agency by having pairs of pianists play the exact same keystrokes (i.e., ambiguous agency) and play one octave apart (i.e., unambiguous agency). The second experiment manipulated agency by having participants listen to excerpts from the first experiment that were performed by the self, the partner, and an unfamiliar participant. Neither experiment yielded any reliable results related to the agency manipulations.

It is possible that there is a generally heightened sense of agency for expert actions (Knoblich & Flach, 2003; Loula et al., 2005; Repp & Knoblich, 2004). Participants in our experiment were highly trained pianists – experts on the piano and in monitoring of piano performance. Experts spend a lot of time training and monitoring their own performance (Ericsson et al., 1993; Ericsson & Lehmann, 1996; Krampe & Ericsson, 1996; Sloboda et al., 1996). Not only does this make them experts in the task they are practicing, but also experts in performance monitoring for that task (Bialystok & DePape, 2009; Chang, 2014; Jentzsch et al., 2014; Palmer & Drake, 1997). Research has shown that music training increases action-perception coupling and strengthens connections between motor movements and auditory outcomes (Novembre & Keller, 2014;

Zatorre et al., 2007). In the experiments reported here, it is likely that pianists were able to maintain self-other distinction without difficulty while monitoring both their own performance and the performance of a partner, and potentially some non-declarative distinction between own and partner's performance over an unfamiliar participant's performance (as reflected in the differences in ERP amplitudes in the second experiment).

It is also possible that the agency manipulation was overlooked in the piano duo task because pitch was a secondary consideration. There is evidence of temporal dominance over pitch in synchronisation tasks (Snyder & Krumhansl, 2001). In the first experiment of this dissertation, pianists were instructed to maintain synchrony with their partner and continue playing if either player made an error. Because of the task instructions, participants may have focused more on timing and therefore focused less on pitch, the dimension that contained the agency manipulation. Further, the pieces selected for this experiment may have contributed to this lack of attention to the pitch aspect. The pieces were repetitive and simple, very easy for highly skilled pianists. Because the pieces were repetitive, participants could easily focus on synchronizing with their partner without attending too closely to the pitches.

It is possible that, because of the instructions to ignore errors and continue playing, participants treated the task as more of a solo task than a duet task. If so, participants may have mostly ignored the partner's performance and focused on their own performance. This could be another explanation for the lack of effect of the agency manipulation. However, participants were also instructed to maintain synchrony with their partner – that was emphasized as the most important part of the task. The reason for ignoring errors and continuing to play was to facilitate the resumption of synchrony between performers. Although there was no direct incentive to play together, participants knew the goal was to play in synchrony. Further, measures of asynchrony shown in the analysis section (Section 2.3.1.3) show that participants did play in synchrony and thus were, at a minimum, monitoring the timing of the partner's performance.

Another possibility of the lack of effect of the agency manipulation is that the task may be using a hybrid of open and closed loops of motor control (Abbs & Gracco, 1984; R. A. Schmidt, 1975; for a full review, see R. A. Schmidt, Lee, Winstein, Wulf, & Zelaznik, 2018). Closed loops rely on feedback to adjust performance, whereas open loops do not rely on feedback (Adams, 1971). It is possible that because synchronicity was the prioritized goal, monitoring of timing was running in a closed loop manner with feedback which would be necessary in order to maintain synchrony with the partner. However, monitoring of the pitches may have been running in an open loop manner, without much feedback. It is assumed that participants would have been maintaining at least a low level of monitoring of the pitches in order to stay in the correct sequential phase relationship with their co-performer. However, the piano pieces were sequential and cyclical, each with its own repeating pattern, and therefore did not need strict monitoring to maintain pitch accuracy (J. R. Anderson, 1993; Beilock & Carr, 2001; Fitts & Posner, 1967). As the agency manipulation was in the pitch domain, reduced monitoring may have left the manipulation unattended. Thus, there was no observed effect of agency ambiguity.

As stated, manipulations of agency were not effective, however the reason for that is not entirely clear. Future work looking to investigate agency in experts should recognise this expert-related advantage of self-other distinction and consider more effective ways of manipulating this factor. Another avenue for future research could use differing instructions for each partner. For example, in a music paradigm, instructions could have one performer (a leader) speed up or slow down so the partner (the follower) has to attend to how the leader is performing their part.

Some studies investigating agency in music performance have used turn-taking paradigms, in which the notes are performed by alternating novice participants (Dell'Anna, Buhmann, Six, Maes, & Leman, 2020; Loehr et al., 2013). However this would be difficult to achieve in a paradigm that is investigating errors in expert musicians performing on their instrument of expertise. The musical material needs to be hard enough to induce errors or needs to be played fast enough to induce errors. Requiring performers to play alternating notes adds another level of complexity and introduces a style of playing that is uncommon. These additional factors increase the difficulty of the task and may reduce participants' ability to do the task. Another possible paradigm could involve a similar paradigm to the first experiment reported here but with an audio feedback swap instead of an octave/unison manipulation, similar to the paradigm used by Knoblich and Repp (2009). That is, participants could play in unison during every trial, but only hear one participant's playing (either their own or their partner's). At the end of the trial, participants could be asked whose performance they were hearing. However, this could add another level of difficulty and complexity to the design and it may not lead to synchronous performance. Research shows that temporal delays are often used to distort a sense of agency (Tian & Poeppel, 2014; Weiss et al., 2014), but this is difficult to implement in a paradigm that relies heavily on synchronicity. As discussed earlier, it is possible that the level of self-monitoring required to achieve expertise in music performance increases self-other distinction so that musicians are very adept at distinguishing their own performance from others.

The ecological nature of the task in the first experiment could be called into question. From a Western classical music perspective, playing simple, one-handed, repetitive musical pieces in a unison or octave duet is not a regularly performed task. However, for highly skilled pianists, playing piano is a regular task and playing simple, repetitive musical phrases is a regular feature of piano practice, whether practicing technical exercises, such as scale patterns or arpeggios, or rigorously rehearsing a challenging passage of a piece (Ericsson, 2018; Ericsson et al., 1993; Lehmann & Ericsson, 1997; Maynard, 2006). Although this type of practice rarely includes practicing with a partner (an exception may be practicing along with a teacher), for the purposes of the first experiment, there had to be some compromise in the choice of stimuli for this task. Perhaps a more ecologically valid task would have less repetitive and simple music. However, more complex, non-repetitive music was used in the pilot testing of the experiment and participants could not recover after making an error. Playing in unison and octaves allowed for participants to re-synchronize with their partner after making an error and missing some notes, maximizing the number of notes played and thus increasing the number of isolated errors. Although the context of a unison and octave duets are not a common task for highly skilled pianists, the repetitive, simple music and the task of playing on a piano keyboard are both common for highly skilled pianists. Future research would benefit from more complex music material (i.e., non-unison and non-octave duets) and a more naturalistic performing context (i.e., in which participants can see each other), but these benefits should be balanced with the ability to obtain isolated errors and the consideration of the time participants would need to rehearse the music.

Another limitation was task difficulty in the second experiment. It was expected that participants would be able to recognise their own performance at levels better than chance, as has been demonstrated previously in piano performance (Keller et al., 2007; Repp & Knoblich, 2004). However, participants' accuracy was not significantly different from chance levels when indicating who performed the excerpt. The excerpts may have been too short for participants to be able to identify the performer. Alternatively, the conditions under which the previous performance was played may have made identification more difficult. The previous piano studies involving performance recognition only investigated past solo piano performance (Keller et al., 2007; Repp & Knoblich, 2004), although performance recognition by pianists in

Keller, et al. (2007) was indicated after the pianists played duets with past self and other recordings. Solo performance allows for more expressive timing that can be used as a cue for self-recognition. In synchronous duo performance, partners presumably need to keep their timing relatively regular and reduce their variability to increase interpersonal coordination (Vesper et al., 2011). Although participants were not able to declaratively recognise the performance, the EEG results did reveal the possibility that performance by an unfamiliar participant and performances that participants indicated were performed by an unfamiliar participant were processed differently than performances by the self and the partner and performances that participants indicated were self-produced.

It was also expected that participants may be able to detect pitch errors in the excerpts, but the responses were biased to responding that there was no error in the excerpt. It is possible that the excerpts were too short for participants to be able to recognise which piece was being performed and thus they would not be able to identify errors, especially because the excerpts could have started at any point in a given piece. The stimuli for the second experiment came from the performances in the first experiment and there were limited options of errors that had 10 correct notes before the error. Thus, the stimuli were short, but it would have been difficult to find excerpts with additional correct notes before error notes, limiting stimuli further. Future work should try to use stimuli that may be longer or have an identifiable starting point so that participants may be better able to identify errors within the performance.

It should be noted that five participants in the experiments were older adults (aged 60 or older at the time of the first experiment). Two of those participants were excluded from all analyses in the first experiment due to a low number of errors in at least one condition and were not participants in the second experiment. The overall behavioural and EEG data analyses were carried out on the data with these participants excluded and the results did not change. All of these participants (including those excluded from the analyses) self-reported as professional or semi-professional musicians, with a minimum of 44 years of experience playing piano. Further, all participants self-reported as practicing piano for at least one hour per day. Research has shown that expert pianists do not demonstrate age-related decline when performing music-related tasks and are only slightly out-performed by younger experts (Horton, Baker, & Schorer, 2008; Krampe & Ericsson, 1996; Meinz, 2000). The lack of age-related decline is thought to be related to deliberate practice during later adulthood (Krampe & Ericsson, 1996). Thus, data from the older participants were retained in the study.

4.4 Current Results with Respect to Literature

4.4.1 Contribution to Error Processing Literature

The first experiment highlighted the importance of error type in how the error is processed. Not all errors are alike. Errors that resulted from an incorrect motor plan with no corrective action (i.e., wrong note errors) showed the same pattern found in previous solo piano studies (Maidhof et al., 2009;

Ruiz et al., 2009). These errors elicited a pre-ERN and a Pe. Behaviourally, these errors were preceded by inconsistent keystroke velocity and resulted in post-error slowing. Synchrony with the partner was reduced during wrong note error sequences compared to correct note sequences and extra note error sequences. Taken together, these results demonstrate a breakdown in performance and can be seen as an extension of the adaptive orienting theory (Wessel, 2018; Wessel & Aron, 2017). As highly skilled actions are automated (J. R. Anderson, 1993; Beilock & Carr, 2001; Fitts & Posner, 1967), performance variability may draw attention to the automated actions, which further degrades performance (Beilock et al., 2008; Beilock et al., 2004; Beilock et al., 2002; Yarrow et al., 2009). Further, research in monkeys has shown that switching from an automated action to a controlled action increases the rate of errors and reaction time (Isoda & Hikosaka, 2007). Thus, the variability in performance would be considered an unexpected action outcome, leading to global motor suppression as shown by post-error slowing. Performance variability may also force a switch from automation to a controlled action, resulting in an increased chance of committing an error and slower action. Therefore, the pre-ERN may be processing the initiation of the error motor command that is foreshadowed by the variability in performance and made more likely by the switch from an automated action to a controlled action. These findings may extend to error processing for more general tasks that are likewise automated, such as walking, driving, or speaking (Chapman, Ismail, & Underwood, 1999; Kapatsinski, 2010).

Errors resulting from a delayed correct response (i.e., extra note errors) provide a slightly different story. In this case, the error resulted in pre-error slowing, and error and post-error speeding, with participants playing two keystrokes in the time of an average correct keystroke. Extra note errors elicited the ERN followed by the Pe. These errors can be understood as delayed correct responses because it is likely that the motor plan for the correct response was develop in parallel with the error response (Rabbitt, 2002; Rodríguez-Fornells et al., 2002; Ullsperger & von Cramon, 2006; Wolpert & Kawato, 1998; Yeung et al., 2004).

Taken together, these findings also partially support the adaptive orienting theory (Wessel, 2018; Wessel & Aron, 2017). The corrective action was implemented within the timeframe of a single keystroke of the partner. This demonstrates that the error response was suppressed quickly enough to allow for corrective action within the strict time constraints. Thus, the global suppression suggested by Wessel and colleagues (2017, 2018) is accounted for; however the adaptive orienting theory does not account for the quick corrective actions following the error.

The conflict monitoring theory (Botvinick et al., 2004; Carter et al., 1998) may account for the quick corrective action observed following extra note errors. In the conflict monitoring theory, competing motor responses are activated, creating a conflict as to which is the correct motor response to carry out. Although conflict monitoring has been dissociated from error processing (Burle et al., 2008; Garavan et al., 2003; Iannaccone et al., 2015; Ullsperger, Danielmeier, et al., 2014), I would suggest that the response conflict is accounting for the corrective action, as opposed to the error processing. As suggested earlier, it is likely that the competing motor responses were developed internally in parallel, with the correct response carried out at a slight delay compared to the incorrect response. This would result in an error followed by a quick correction, as observed in the extra note errors. The errors then present as finger slips, as the incorrect keystrokes were neighbouring keystrokes from the correct keystrokes. A more general example of this would be missing a step while going down stairs or doing the awkward back-and-forth shuffle when trying to avoid an oncoming pedestrian while walking on a busy sidewalk. The competing motor responses can cause indecision and even full motor stoppage, but if a correct motor response is already developed, further consequences from the error can be minimised or even avoided.

Further, errors with and without pre-response conflict activate distinct cortical areas (Wittfoth et al., 2008). In an fMRI experiment, errors with pre-response conflict distinctly elicited increased activation in the rostral anterior cingulate cortex and the precuneus, while errors without pre-response conflict distinctly elicited increased activation in the right inferior parietal cortex (Wittfoth et al., 2008). Keeping in mind the limitations of localisation with EEG (even with source estimation, which was not conducted in the current study), the results presented here from the extra note and wrong note errors do correspond to the patterns of activation found for errors with and without pre-response conflict. Extra note errors (i.e., errors with pre-response conflict) elicited increased ERN amplitude in the middle anterior region of interest – an area that is consistent with a source in the rostral anterior cingulate cortex. Wrong note errors (i.e., errors without pre-response conflict) elicited increased pre-ERN amplitude in the right centre and right posterior regions of interest – areas that are consistent with the right inferior parietal cortex. Thus, while speculative, the regions of interest that elicited increased activity for extra note errors and wrong note errors correspond to likely cortical areas associated with errors committed with and without pre-response conflict, respectively.

Using an ecological task with expert performers allowed for this unexpected exploration of error types. As the task was highly learned and had become automatic, I have suggested that the wrong note errors are an example of performance breakdown preceded and foreshadowed by increased variability in performance. This variability shifted the processing of these actions from automatic to controlled, further degrading the level of performance (Beilock et al., 2008; Beilock et al., 2004; Beilock et al., 2002; Isoda & Hikosaka, 2007; Yarrow et al., 2009). As extra note errors were followed by quick corrections, I have suggested that these errors are an example of delayed correct responses and result from response conflict. The errors were neighbouring notes from the correct notes, which suggests there was some uncertainty about the correct note to play at that time. The uncertainty is also reflected in the reduced velocity on these keystrokes. The delayed correct response followed the error so closely that it is unlikely to be an intentional action, but more likely automatic, unreflective responses

(Rabbitt et al., 1978; Ullsperger, Danielmeier, et al., 2014; Yeung & Summerfield, 2012).

4.4.2 Contribution to Joint Action and Agency Literature

The first experiment demonstrated that errors of a partner did not affect one's own performance in highly trained pianists. Partners were instructed to play in synchrony and to continue if either player made an error. These instructions may have made it less likely for partner errors to affect performers. Errors of a partner did elicit the FRN, as expected from previous literature on observed errors (Loehr et al., 2013; Nieuwenhuis, Holroyd, et al., 2004). Asynchrony data showed that pairs were less synchronous when leading up to, while playing, and after playing wrong note errors compared to playing correct notes or extra note errors. The manipulations of agency did not show any significant effects in the first experiment. This suggests that even in joint action and when agency is ambiguous, highly trained pianists are able to distinguish between their own performance and the performance of others.

Models of joint action suggest that during joint action, performers develop internal models for both their own and co-performers actions (Keller et al., 2016; Pesquita et al., 2018). It was suggested earlier in this dissertation that agency ambiguity during joint action may cause an overlap in self and other internal models. Expertise in a particular action may help performers resolve the confusion in self-other distinction when agency is ambiguous. Further, as familiarity seemed to play a role in the processing of the perceived excerpts in the second experiment, it is possible that internal models were sensitive to self motor signatures regardless of overlap in pitch, causing both parts to be integrated into one stream. Integration could lead to an increased sense of familiarity for both parts when later encountered perceptually. Overlap of internal models remains a possibility for ambiguous agency during joint actions performed by non-experts.

4.4.3 Contribution to Auditory Processing Literature

Conclusions from the results of the second experiment are speculative; however, they provide an interesting avenue for future research. A decreased feeling of familiarity may increase the amount of cognitive resources allocated to recognising and identifying a stimulus (Morris et al., 2008). It is understood that unfamiliar stimuli are more difficult to process than familiar stimuli (Frith, 1974). In the second experiment, the excerpts played by an unfamiliar participant were somewhat familiar because all participants played the same pieces in the first experiment. However, excerpts by an unfamiliar participant are the only cases that had never been heard by the participant before the second experiment. Thus, participants had the least experience and familiarity with the unfamiliar participant's excerpts. This suggests that there may have been some implicit sense of recognizing the excerpts, yet still not being able to place them. For example, when you see a person who looks familiar, you spend more time and cognitive resources trying to identify the person than if the person was familiar and easy to identify or if the person was a complete stranger. As there is evidence that arousal increases amplitudes in the N1/P2 complex, this increased arousal may result in increased amplitude in the N1 component for the actual stimulus itself and increased amplitude in the P2 when someone thinks there is decreased familiarity. Further, the N1 results suggest that perceptual experience may be sufficient for the partner's excerpts to be processed similarly to self-produced excerpts (Schütz-Bosbach & Prinz, 2007).

Another possibility is that the performance by an unfamiliar participant was the most unexpected. Amplitude of the N1 has been shown to vary by expectancy (Batterink & Neville, 2013; Carrus et al., 2013; Koelsch & Jentschke, 2010; Novembre et al., 2018; Robinson et al., 2019). Performances by an unfamiliar participant were the least familiar, so those excerpts may have elicited increased N1 amplitudes due to increased unexpectedness.

Although the ERP results were not reflected by differences in the behavioural results, they may suggest that the more familiar performances were slightly easier to process than the unfamiliar performances. Future work should further investigate this relationship between familiar and unfamiliar performance and belief of agency.

4.5 Conclusions and Future Work

This research project intended to investigate the role of agency in error processing during both performance and perception. As stated above, the agency manipulations were not effective and thus the conclusions from the data provided narratives unrelated to agency. The design of the first experiment and its ecologically valid task allowed for an exploration of different types of errors. The subtle differences in neural activity while processing those errors can be viewed through an extension of the current theoretical framework for error processing and unexpected events more generally (i.e., the adaptive orienting theory; Wessel, 2018). I have suggested that errors developed out of a breakdown in performance can be processed as soon as the incorrect motor plan is initiated, resulting in error-related neural activity that is elicited and can be observed before the error onset. This is further replication of the results from solo piano performance studies (Maidhof et al., 2009; Ruiz et al., 2009). I have also suggested that errors arising out of response conflict are processed as soon as the action is known to be erroneous, and that these errors do not result in behavioural slowing, but a fast, reactive, corrective response, which can likewise be considered adaptive. The overall findings of the first experiment suggest that through extensive training, skilled individuals develop a sensory-motor system that supports fluent interpersonal coordination in real-time joint action by applying distinct neural mechanisms to manage different types of errors.

Conclusions from the second experiment are speculative, but may provide avenues for future work. Performances that were perceptually more familiar may have been easier to process. Likewise, performances that were thought to be familiar may have been easier to process. More work on belief of agency and performance monitoring needs to be done to further clarify these findings.

One final aspect to consider is the use of an ecological task for this research project. The investigation of different types of errors would not have been possible with a standard discrete task. Similarly, using an ecological task allows for generalizability to other non-specialist well-trained actions, such as walking, driving, or speaking. People are highly proficient in many actions and this study of trained experts performing their expert actions is easily transferred to more mundane tasks of everyday life.

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Appendix A: Musical Pieces for Experiment 1

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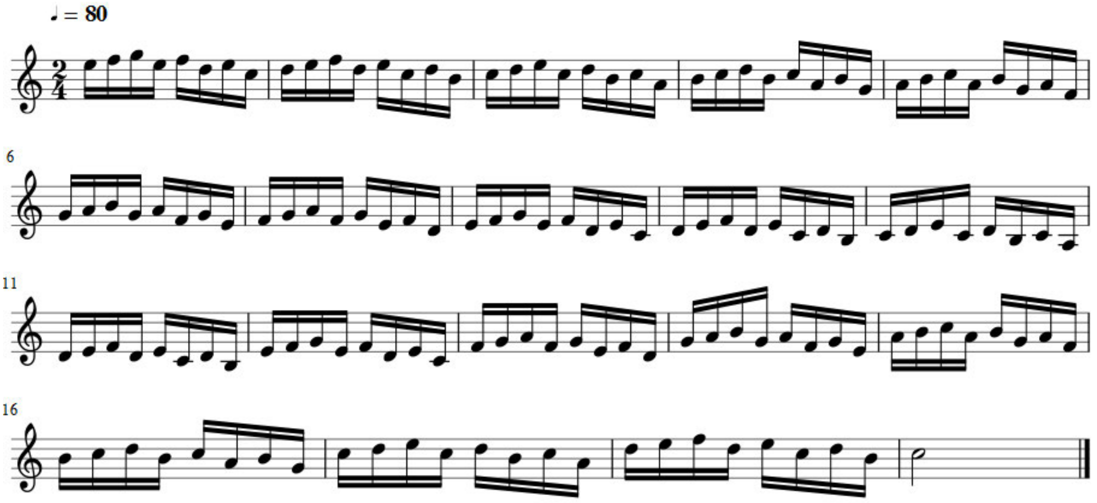
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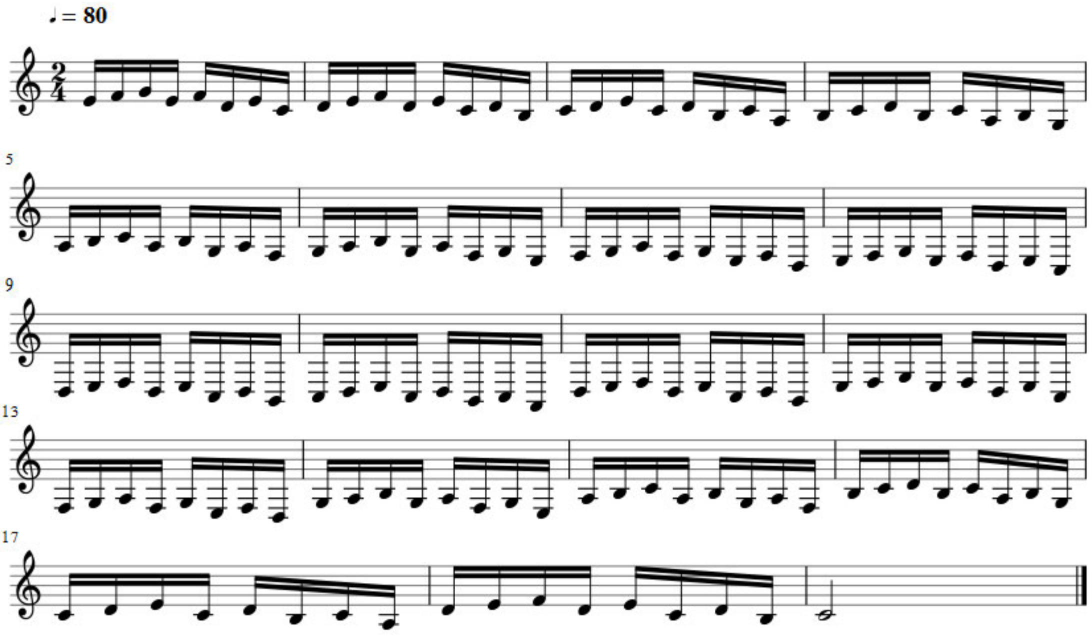
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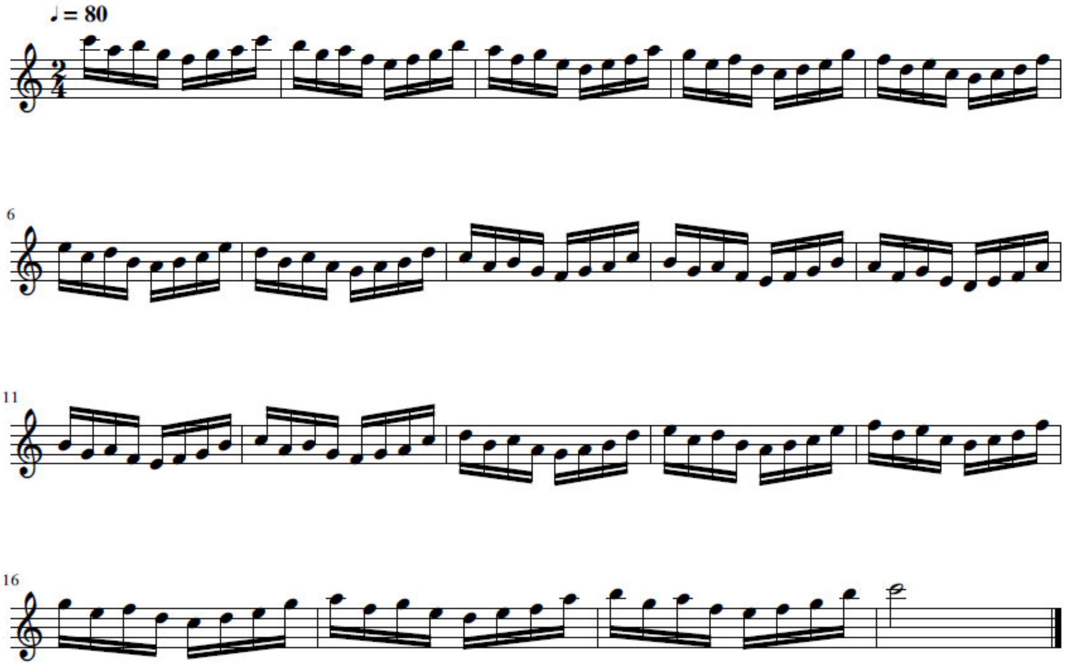
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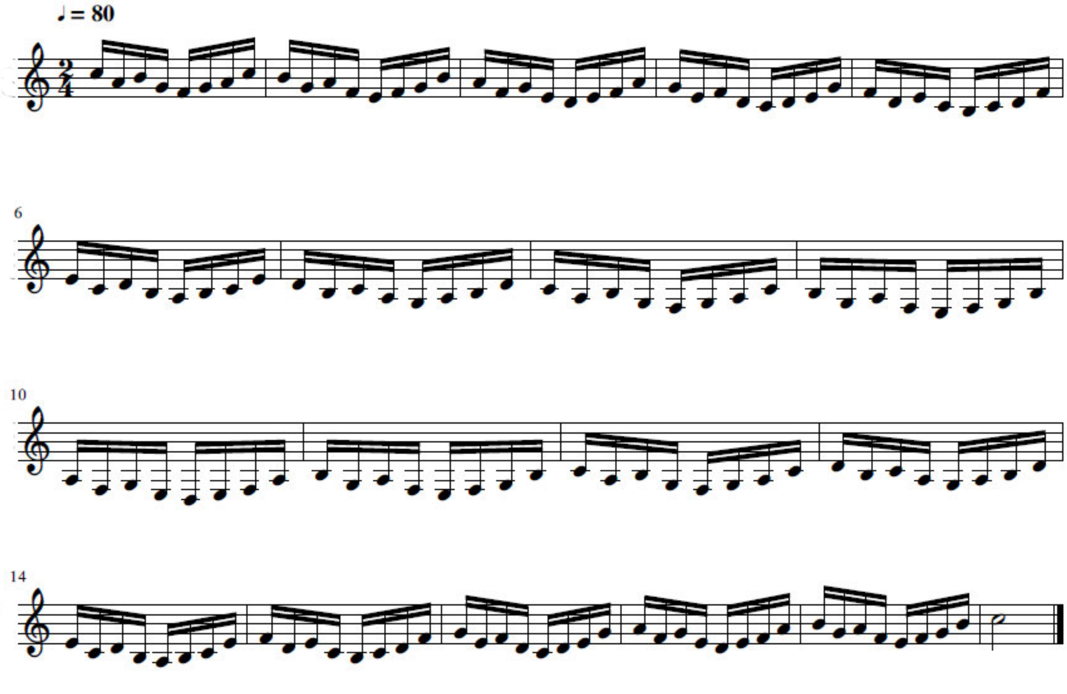
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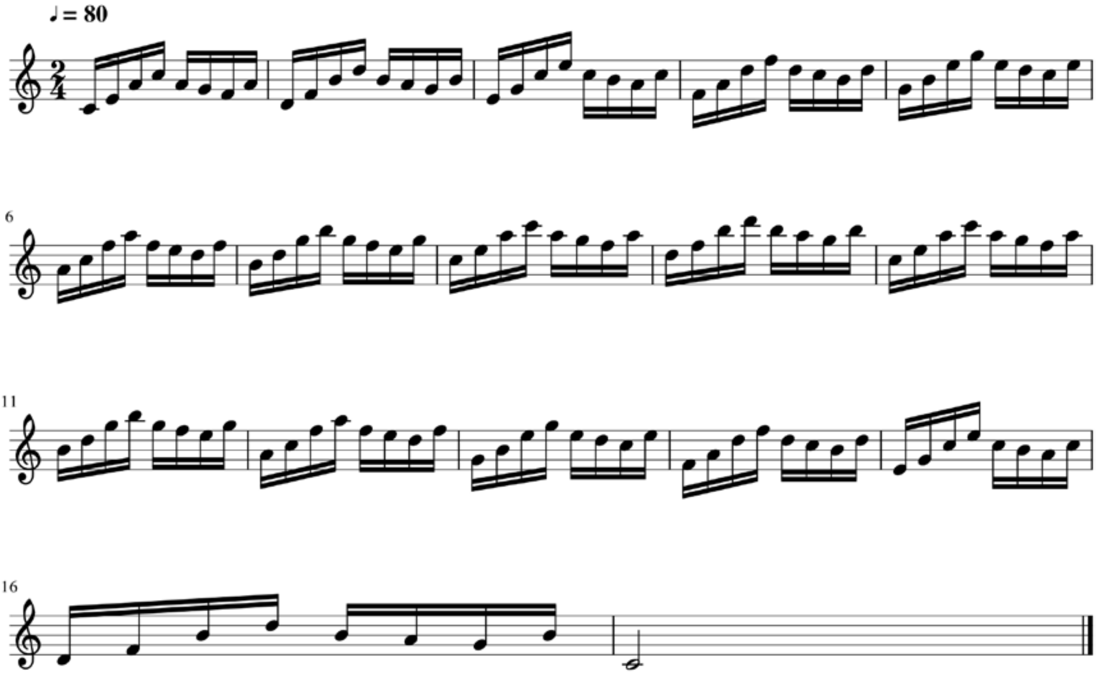
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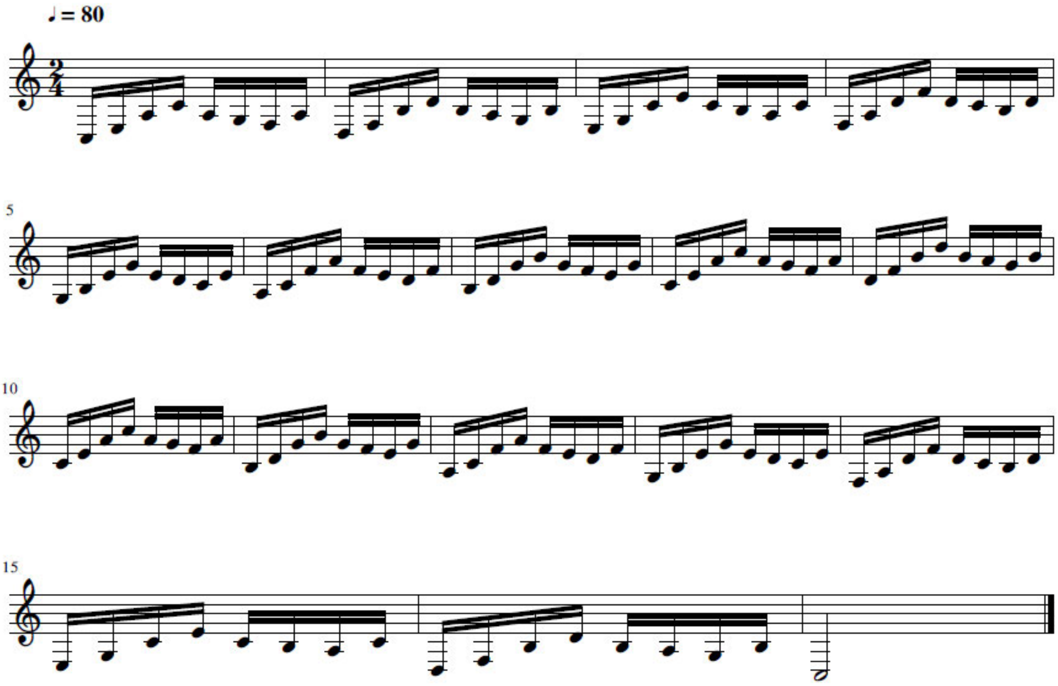
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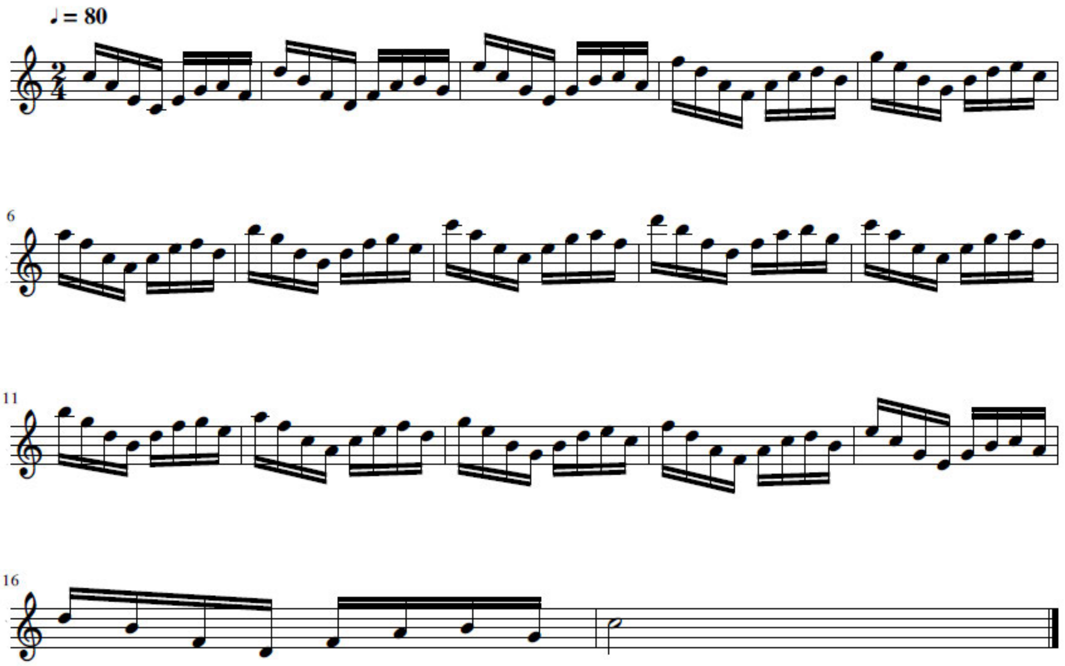
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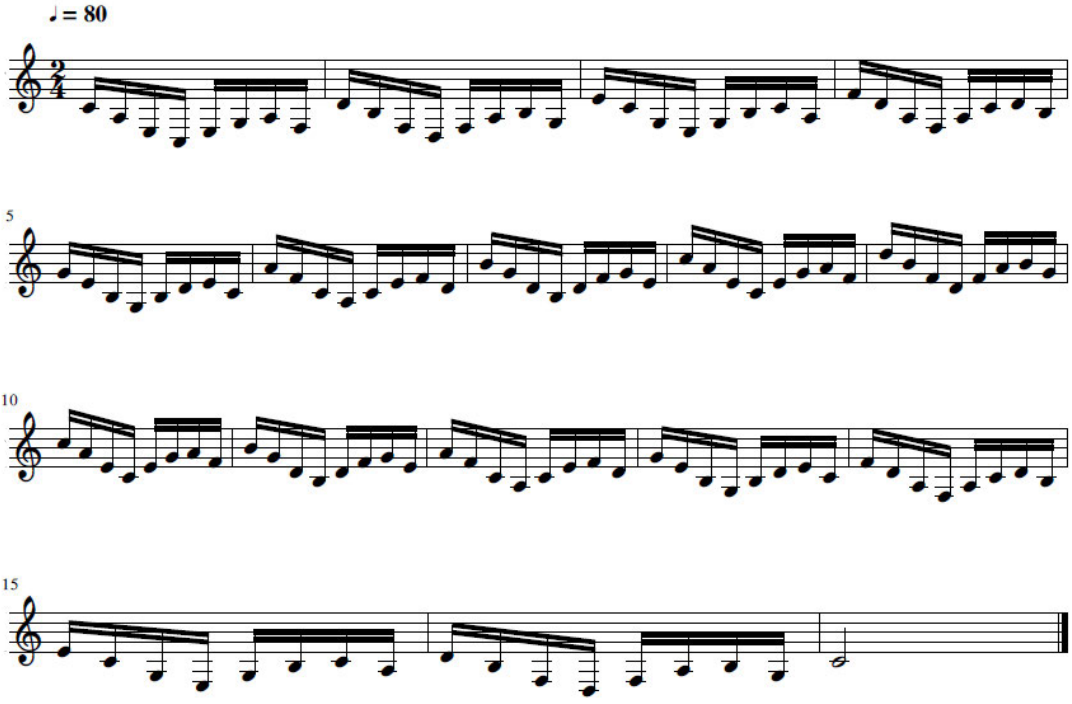
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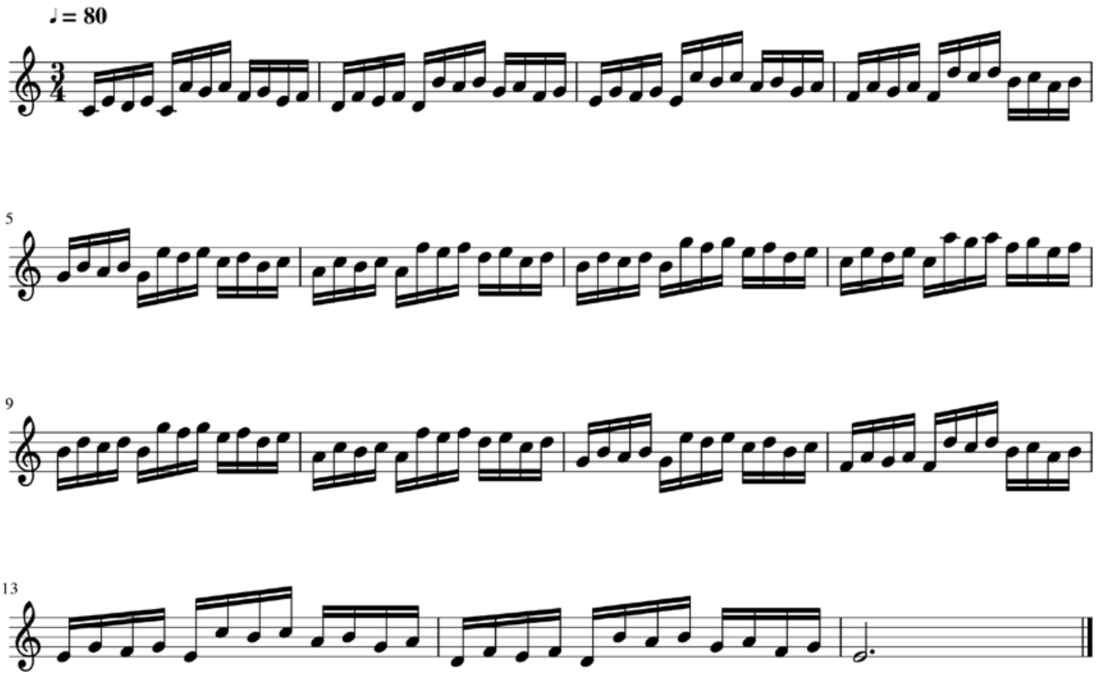
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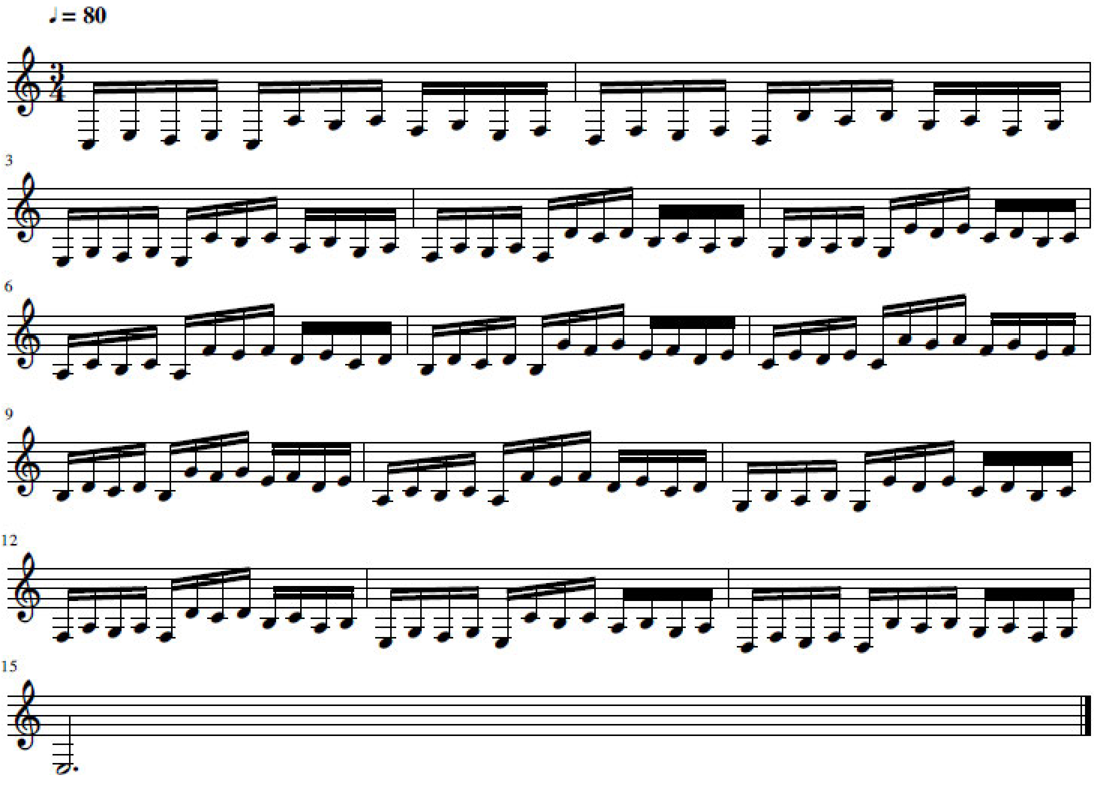
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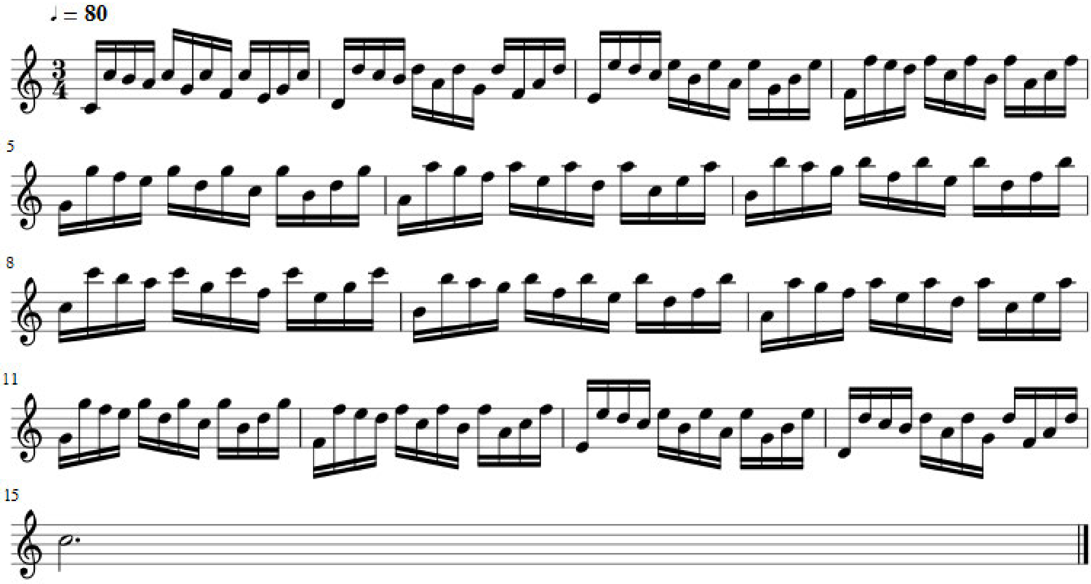
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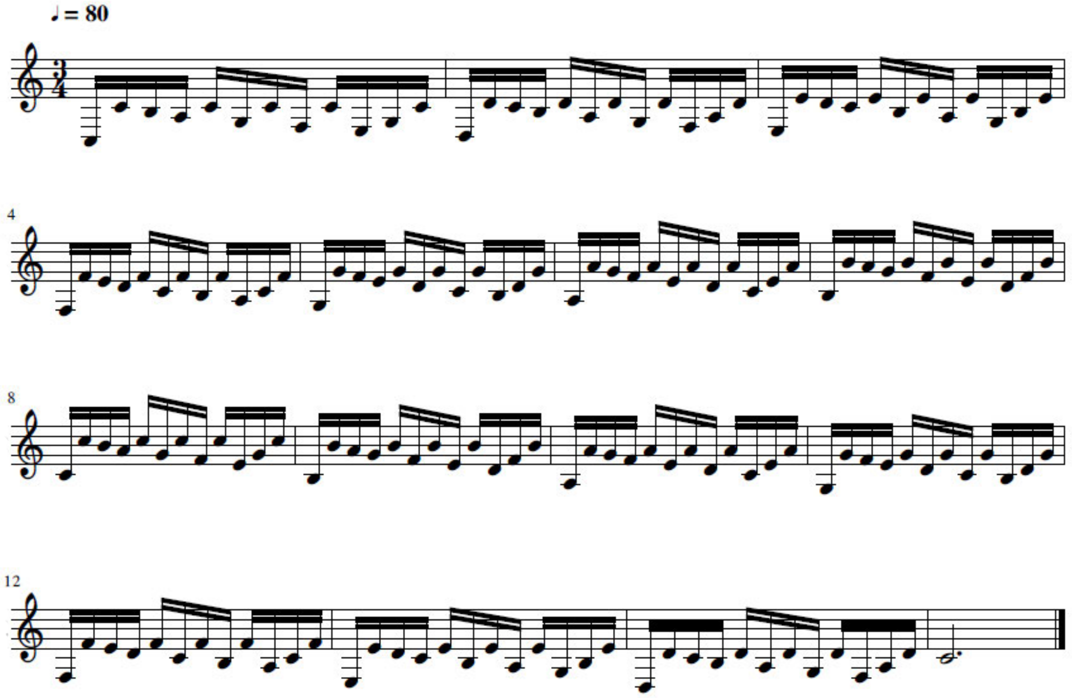

Appendix B: Questionnaire from Experiment 1

General Questions

1. What is your age?

2. What is your sex?

3. What is your handedness?

4. Do you have any hearing impairments?
    a. If yes, please specify the nature of your hearing impairment.

Interpersonal Reactivity Index

The following statements inquire about your thoughts and feelings in a variety of situations. For each item, indicate how well it describes you by choosing the appropriate number on the scale.

Please read each item carefully before responding.

1. I daydream and fantasize, with some regularity, about the things that might happen to me.

Does not describe me well				Describes me well
1	2	3	4	5

2. I often have tender, concerned feelings for people less fortunate than me.

Does not describe me well				Describes me well
1	2	3	4	5

3. I sometimes find it difficult to see things from the “other guy’s” point of view.

Does not describe me well				Describes me well
1	2	3	4	5

4. Sometimes I don’t feel very sorry for other people when they are having problems.

Does not describe me well				Describes me well
1	2	3	4	5

5. I really get involved with the feelings of the characters in a novel.

Does not describe me well				Describes me well
1	2	3	4	5

6. In emergency situations, I feel apprehensive and ill-at-ease.

Does not describe me well				Describes me well
1	2	3	4	5

7. I am usually objective when I watch a movie or play, and I don’t often get completely caught up in it.

Does not describe me well				Describes me well
1	2	3	4	5

8. I try to look at everybody’s side of a disagreement before I make a decision.

Does not describe me well				Describes me well
1	2	3	4	5

9. When I see someone being taken advantage of, I feel kind of protective towards them.

Does not describe me well				Describes me well
1	2	3	4	5

10. I sometimes feel helpless when I am in the middle of a very emotional situation.

Does not describe me well				Describes me well
1	2	3	4	5

11. I sometimes try to understand my friends by imagining how things look from their perspective.

Does not describe me well				Describes me well
1	2	3	4	5

12. Becoming extremely involved in a good book or movie is somewhat rare for me.

Does not describe me well				Describes me well
1	2	3	4	5

13. When I see someone get hurt, I tend to remain calm.

Does not describe me well				Describes me well
1	2	3	4	5

14. Other people’s misfortunes do not usually disturb me a great deal.

Does not describe me well				Describes me well
1	2	3	4	5

15. If I’m sure I’m right about something, I don’t waste much time listening to other people’s arguments.

Does not describe me well				Describes me well
1	2	3	4	5

16. After seeing a play or movie, I have felt as though I were one of the characters.

Does not describe me well				Describes me well
1	2	3	4	5

17. Being in a tense emotional situation scares me.

Does not describe me well				Describes me well
1	2	3	4	5

18. When I see someone being treated unfairly, I sometimes don't feel very much pity for them.

Does not describe me well				Describes me well
1	2	3	4	5

19. I am usually pretty effective in dealing with emergencies.

Does not describe me well				Describes me well
1	2	3	4	5

20. I am often quite touched by things that I see happen.

Does not describe me well				Describes me well
1	2	3	4	5

21. I believe that there are two sides to every question and try to look at them both.

Does not describe me well				Describes me well
1	2	3	4	5

22. I would describe myself as a pretty soft-hearted person.

Does not describe me well				Describes me well
1	2	3	4	5

23. When I watch a good movie, I can very easily put myself in the place of a leading character.

Does not describe me well				Describes me well
1	2	3	4	5

24. I tend to lose control during emergencies.

Does not describe me well				Describes me well
1	2	3	4	5

25. When I’m upset at someone, I usually try to “put myself in his shoes” for a while.

Does not describe me well				Describes me well
1	2	3	4	5

26. When I am reading an interesting story or novel, I imagine how I would feel if the event in the story were happening to me.

Does not describe me well				Describes me well
1	2	3	4	5

27. When I see someone who badly needs help in an emergency, I go to pieces.

Does not describe me well				Describes me well
1	2	3	4	5

28. Before criticizing someone, I try to imagine how I would feel if I were in their place.

Does not describe me well				Describes me well
1	2	3	4	5

Big Five Inventory

How well do the following statements describe your personality? For each item, indicate how well it describes you by choosing the appropriate number on the scale.

1. I see myself as someone who is reserved.

Strongly Disagree				Strongly Agree
1	2	3	4	5

2. I see myself as someone who is generally trusting.

Strongly Disagree				Strongly Agree
1	2	3	4	5

3. I see myself as someone who tends to be lazy.

Strongly Disagree				Strongly Agree
1	2	3	4	5

4. I see myself as someone who is relaxed, handles stress well.

Strongly Disagree				Strongly Agree
1	2	3	4	5

5. I see myself as someone who has few artistic interests.

Strongly Disagree				Strongly Agree
1	2	3	4	5

6. I see myself as someone who is outgoing, sociable.

Strongly Disagree				Strongly Agree
1	2	3	4	5

7. I see myself as someone who tends to find fault with others.

Strongly Disagree				Strongly Agree
1	2	3	4	5

8. I see myself as someone who does a thorough job.

Strongly Disagree				Strongly Agree
1	2	3	4	5

9. I see myself as someone who gets nervous easily.

Strongly Disagree				Strongly Agree
1	2	3	4	5

10. I see myself as someone who has an active imagination.

Strongly Disagree				Strongly Agree
1	2	3	4	5

Core Self-Evaluations Scale

Below are several statements about you with which you may agree or disagree. For each item, indicate your agreement or disagreement with each item by choosing the appropriate number on the scale.

1. I am confident I get the success I deserve in life.

Strongly Disagree				Strongly Agree
1	2	3	4	5

2. Sometimes I feel depressed.

Strongly Disagree				Strongly Agree
1	2	3	4	5

3. When I try, I generally succeed.

Strongly Disagree				Strongly Agree
1	2	3	4	5

4. Sometimes when I fail, I feel worthless.

Strongly Disagree				Strongly Agree
1	2	3	4	5

5. I complete tasks successfully.

Strongly Disagree				Strongly Agree
1	2	3	4	5

6. Sometimes, I do not feel in control of my work.

Strongly Disagree				Strongly Agree
1	2	3	4	5

7. Overall, I am satisfied with myself.

Strongly Disagree				Strongly Agree
1	2	3	4	5

8. I am filled with doubts about my competence.

Strongly Disagree				Strongly Agree
1	2	3	4	5

9. I determine what will happen in my life.

Strongly Disagree				Strongly Agree
1	2	3	4	5

10. I do not feel control of my success in my career.

Strongly Disagree				Strongly Agree
1	2	3	4	5

11. I am capable of coping with most of my problems.

Strongly Disagree				Strongly Agree
1	2	3	4	5

12. There are times when things look pretty bleak and hopeless to me.

Strongly Disagree				Strongly Agree
1	2	3	4	5

Liebowitz Social Anxiety Scale

Read each situation carefully and answer two questions about that situation.
The first question asks how anxious or fearful you feel in the situation.
The second question asks how often you avoid the situation.
If you come across a situation that you ordinarily do not experience, we ask that you imagine "what if you were faced with that situation", and then rate the degree to which you would fear this hypothetical situation and how often you would tend to avoid it. Please base your ratings on the way the situations have affected you in the last week.

0 = none
1 = mild
2 = moderate
3 = severe

	Fear				Avoid			
Using a telephone in public	0	1	2	3	0	1	2	3
Participating in small group activity	0	1	2	3	0	1	2	3
Eating in public	0	1	2	3	0	1	2	3
Drinking with others	0	1	2	3	0	1	2	3
Talking to someone in authority	0	1	2	3	0	1	2	3
Acting, performing, or speaking in front of an audience	0	1	2	3	0	1	2	3
Going to a party	0	1	2	3	0	1	2	3
Working while being observed	0	1	2	3	0	1	2	3
Writing while being observed	0	1	2	3	0	1	2	3
Calling someone you don't know very well	0	1	2	3	0	1	2	3
Talking face to face with someone you don't know very well	0	1	2	3	0	1	2	3
Meeting strangers	0	1	2	3	0	1	2	3
Urinating in a public bathroom	0	1	2	3	0	1	2	3
Entering a room when others are already seated	0	1	2	3	0	1	2	3
Being the centre of attention	0	1	2	3	0	1	2	3
Speaking up at a meeting	0	1	2	3	0	1	2	3
Taking a test of your ability, skill, or knowledge	0	1	2	3	0	1	2	3
Expressing disagreement or disapproval to someone you don't know very well	0	1	2	3	0	1	2	3
Looking someone who you don't know very well straight in the eyes	0	1	2	3	0	1	2	3
Giving a prepared oral talk to a group	0	1	2	3	0	1	2	3
Trying to make someone's acquaintance for the purpose of a romantic/sexual relationship	0	1	2	3	0	1	2	3
Returning goods to a store for a refund	0	1	2	3	0	1	2	3
Giving a party	0	1	2	3	0	1	2	3
Resisting a high pressure sales person	0	1	2	3	0	1	2	3

Locus of Control

The following is a series of attitude statements. Each represents a commonly held opinion. There are no right or wrong answers. You will probably agree with some items and disagree with others. We are interested in the extent to which you agree or disagree with such matters of opinion. Read each statement carefully. Then indicate the extent to which you agree or disagree by selecting the appropriate response. Please answer every question as honestly as possible.

1. Whether or not I get to be a leader depends mostly on my ability.

   ○ Strongly disagree
   ○ Somewhat disagree
   ○ Slightly disagree
   ○ Slightly agree
   ○ Somewhat agree
   ○ Strongly agree

2. To a great extent my life is controlled by accidental happenings.

   ○ Strongly disagree
   ○ Somewhat disagree
   ○ Slightly disagree
   ○ Slightly agree
   ○ Somewhat agree
   ○ Strongly agree

3. I feel like what happens in my life is mostly determined by powerful people.

   ○ Strongly disagree
   ○ Somewhat disagree
   ○ Slightly disagree
   ○ Slightly agree
   ○ Somewhat agree
   ○ Strongly agree

4. Whether or not I get into a car accident depends mostly on how good a driver I am.

    ○ Strongly disagree
    ○ Somewhat disagree
    ○ Slightly disagree
    ○ Slightly agree
    ○ Somewhat agree
    ○ Strongly agree

5. When I make plans, I am almost certain to make them work.

    ○ Strongly disagree
    ○ Somewhat disagree
    ○ Slightly disagree
    ○ Slightly agree
    ○ Somewhat agree
    ○ Strongly agree

6. Often there is no chance of protecting my personal interests from bad luck happenings.

    ○ Strongly disagree
    ○ Somewhat disagree
    ○ Slightly disagree
    ○ Slightly agree
    ○ Somewhat agree
    ○ Strongly agree

7. When I get what I want, it is usually because I’m lucky.

    ○ Strongly disagree
    ○ Somewhat disagree
    ○ Slightly disagree
    ○ Slightly agree
    ○ Somewhat agree
    ○ Strongly agree

8. Although I might have good ability, I will not be given leadership responsibility without appealing to those in positions of power.

    ○ Strongly disagree
    ○ Somewhat disagree
    ○ Slightly disagree
    ○ Slightly agree
    ○ Somewhat agree
    ○ Strongly agree

9. How many friends I have depends on how nice a person I am.

    ○ Strongly disagree
    ○ Somewhat disagree
    ○ Slightly disagree
    ○ Slightly agree
    ○ Somewhat agree
    ○ Strongly agree

10. I have often found that what is going to happen will happen.

    ○ Strongly disagree
    ○ Somewhat disagree
    ○ Slightly disagree
    ○ Slightly agree
    ○ Somewhat agree
    ○ Strongly agree

11. My life is chiefly controlled by powerful others.

    ○ Strongly disagree
    ○ Somewhat disagree
    ○ Slightly disagree
    ○ Slightly agree
    ○ Somewhat agree
    ○ Strongly agree

12. Whether or not I get into a car accident is mostly a matter of luck.

○ Strongly disagree
○ Somewhat disagree
○ Slightly disagree
○ Slightly agree
○ Somewhat agree
○ Strongly agree

13. People like myself have very little chance of protecting our personal interests when they conflict with those of strong pressure groups.

○ Strongly disagree
○ Somewhat disagree
○ Slightly disagree
○ Slightly agree
○ Somewhat agree
○ Strongly agree

14. It’s not always wise for me to plan too far ahead because many things turn out to be a matter of good or bad fortune.

○ Strongly disagree
○ Somewhat disagree
○ Slightly disagree
○ Slightly agree
○ Somewhat agree
○ Strongly agree

15. Getting what I want requires pleasing those people above me.

○ Strongly disagree
○ Somewhat disagree
○ Slightly disagree
○ Slightly agree
○ Somewhat agree
○ Strongly agree

16. Whether or not I get to be a leader depends on whether I’m lucky enough to be in the right place at the right time.

    - ○ Strongly disagree
    - ○ Somewhat disagree
    - ○ Slightly disagree
    - ○ Slightly agree
    - ○ Somewhat agree
    - ○ Strongly agree

17. If important people were to decide they didn’t like me, I probably wouldn’t make many friends.

    - ○ Strongly disagree
    - ○ Somewhat disagree
    - ○ Slightly disagree
    - ○ Slightly agree
    - ○ Somewhat agree
    - ○ Strongly agree

18. I can pretty much determine what will happen in my life.

    - ○ Strongly disagree
    - ○ Somewhat disagree
    - ○ Slightly disagree
    - ○ Slightly agree
    - ○ Somewhat agree
    - ○ Strongly agree

19. I am usually able to protect my personal interests.

    - ○ Strongly disagree
    - ○ Somewhat disagree
    - ○ Slightly disagree
    - ○ Slightly agree
    - ○ Somewhat agree
    - ○ Strongly agree

20. Whether or not I get into a car accident depends mostly on the other driver.

○ Strongly disagree
○ Somewhat disagree
○ Slightly disagree
○ Slightly agree
○ Somewhat agree
○ Strongly agree

21. When I get what I want, it’s usually because I worked hard for it.

○ Strongly disagree
○ Somewhat disagree
○ Slightly disagree
○ Slightly agree
○ Somewhat agree
○ Strongly agree

22. In order to have my plans work, I make sure that they fit in with the desires of people who have power over me.

○ Strongly disagree
○ Somewhat disagree
○ Slightly disagree
○ Slightly agree
○ Somewhat agree
○ Strongly agree

23. My life is determined by my own actions.

○ Strongly disagree
○ Somewhat disagree
○ Slightly disagree
○ Slightly agree
○ Somewhat agree
○ Strongly agree

24. It’s chiefly a matter of fate whether or not I have few friends or many friends.

    ○ Strongly disagree
    ○ Somewhat disagree
    ○ Slightly disagree
    ○ Slightly agree
    ○ Somewhat agree
    ○ Strongly agree

Ollen Musical Sophistication Index

Please answer every question (unless you are directed to skip one) as honestly and accurately as possible.

1. At what age did you begin sustained musical activity? “Sustained musical activity” might include regular music lessons or daily musical practice that lasted for at least three consecutive years. If you have never been musically active for a sustained time period, answer with 0.

   Age at start of sustained musical activity? _______________

2. 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 you’ve studied the longest and specify the instrument. If you have never received private music lessons, answer with 0.

   Years of private lessons? _____________
   Which instrument? _____________

3. For how many years have you engaged in regular, daily practice of a musical instrument? “Daily” can be defined as 5 to 7 days per week. A “year” can be defined as 10 to 12 months. If you have never practised regularly, or have practised regularly for fewer than 10 months, answer with 0.

   Years of regular practice? _____________

4. Which category comes nearest to the amount of time you currently spend practising an instrument (including voice)? Count individual practice time only, not group rehearsals. Please highlight your response.

   ○ I rarely or never practise 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

5. Have you ever enrolled in any music courses offered at college (or university)?

   ○ Yes
   ○ No

   a. If yes, how much college-level coursework in music have you completed? If more than one category applies, select your most recently completed level.

      ○ None
      ○ 1 or 2 NON-major course (e.g., music appreciation, playing, or singing in an ensemble)
      ○ 3 or more courses for NON-majors
      ○ An introductory or preparatory music program for Bachelor’s level work
      ○ 1 year of full-time coursework in a Bachelor of Music degree program (or equivalent)
      ○ 2 years of full-time coursework in a Bachelor of Music degree program (or equivalent)
      ○ 3 or more years of full-time coursework in a Bachelor of Music degree program (or equivalent)
      ○ Completion of a Bachelor of Music degree program (or equivalent)
      ○ One or more graduate-level music course or degrees

6. 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 completed 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)

7. 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 past 12 months? 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

8. What title best describes you?

○ Non-musician
○ Music-loving non-musician
○ Amateur musician
○ Serious amateur musician
○ Semi-professional musician
○ Professional musician

Study-related Questions

1. How many years have you played the piano (continuously)? ________

2. What age did you start playing the piano? __________

3. How often do you currently play the piano (in hours per week)? _______

4. Do you have experience playing piano duets?

    ○ Yes
    ○ No

    a. If yes, how many hours per week do you play piano duets? _______

5. Do you have experience playing in ensembles?

    ○ Yes
    ○ No

    a. If yes, please indicate on what instruments and the frequency in hours per week (for example, violin, 2; flute, 1.5; guitar, 3).

    ____

6. When did you start practising the exercises? _____________

7. What days did you practise these exercises?

    ○ Monday
    ○ Tuesday
    ○ Wednesday
    ○ Thursday
    ○ Friday
    ○ Saturday
    ○ Sunday

8. On the days you did practise the exercises, approximately how long did you practise (in minutes)? ______________

9. Did you practise all exercises with the same frequency?

    ○ Yes
    ○ No

a. If no, please select the exercises you practised more.

- ○ A
- ○ B
- ○ C
- ○ D
- ○ E
- ○ F

10. Please select any of the exercises that you were familiar with before the study.

- ○ A
- ○ B
- ○ C
- ○ D
- ○ E
- ○ F
- ○ None

11. Do you feel you synchronized better with your partner when playing in unison or in octaves?

- ○ Unison
- ○ Octaves
- ○ No difference

12. Who do you think made more errors overall?

- ○ You
- ○ Your partner
- ○ Both made same amount of errors

13. Did you have any difficulties playing with your partner?

- ○ Yes
- ○ No

a. If yes, what made it difficult?

____

14. Were you able to hear and distinguish your own playing from your partner’s playing?

  - ○ Yes, all the time
  - ○ Only when playing in octaves
  - ○ No, not consistently

Appendix C: Questionnaire from Experiment 2

Questionnaire

1. What is your age? _____________
2. What is your gender? __________
3. How many years of formal piano lessons have you taken? _________
4. a. In the previous experiment, was your partner someone you knew before the experiment? __________

   b. If yes, how do you know your partner from the previous experiment?
   ____
5. In the previous experiment, who made more errors – you or your partner?
   ____
6. Do you think you were accurate in recognising your own performance compared to your partner's and the unfamiliar player's?
   ____
7. Do you think you were accurate in recognising your partner's performance compared to the unfamiliar player's? ______________________________
8. Did you notice the errors in the excerpts you heard? ___________________