Motor Interference and Behaviour Adaptation in Human-Humanoid Interactions

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Abstract

This thesis proposes and experimentally demonstrates an approach enabling a humanoid robot to adapt its behaviour to match a human's behaviour in real-time human-humanoid interaction. The approach uses the information distance synchrony detection method, which is a novel method to measure the behaviour synchrony between two agents, as the core part of the behaviour adaptation mechanism to guide the humanoid robot to change its behaviour in the interaction. The feedback of the participants indicated that the application of this behaviour adaptation mechanism could facilitate human-humanoid interaction. The investigation of motor interference, which may be adopted as a possible metric to quantify the social competence of a robot, is also presented in this thesis. The results from two experiments indicated that both human participants' beliefs about the engagement of the robot and the usage of rhythmic music might affect the elicitation of the motor interference effects. Based on these findings and recent research supporting the importance of other features in eliciting the interference effects, it can be hypothesized that the *overall perception* of a humanoid robot as a social entity instead of any individual feature of the robot is critical to elicit motor interference in a human observer's behaviour. In this thesis, the term '*overall perception*' refers to the human observer's overall perception of the robot in terms of appearance, behaviour, the observer's belief and environmental features that may affect the perception. Moreover, it was found in the motor coordination investigation that humans tended to synchronize themselves with a humanoid robot without being instructed to do so. This finding, together with the behaviour adaptation mechanism, may support the feasibility of bi-directional motor coordination in human-humanoid interaction.

Contents

Chapter 1
Introduction

Robots, once only seen in the writings of science fiction authors, are now beginning to become reality. Many would consider that robots are primarily industrial, such as in a modern car factory, where robots can be seen on assembly lines producing vehicles. Other robots rely more closely on human interaction, for example engineers use robots, such as the Mars Rover (Volpe 2007), to explore environments that are inaccessible to human beings. Such robots are also used in dangerous situations such as explosives dismantlement (Scholtz et al. 2006) and nuclear power plant decommissioning (Bakari et al. 2006). There is, however, another class of robots which has more social characteristics and might be considered to have more humanlike features. These are called companion and assistant robots. Examples include Paro (Wada et al. 2004) which was used as a therapeutic companion helping people with Dementia and Alzheimer's and KASPAR (Robins et al. 2004) which was used in research with Autistic spectrum children. A key aspect of this latter class of robots is their social competence, which can be defined as the competence in interaction with a human and can include factors such as empathy, communication effectiveness and interaction synchrony with a human (Waters and Sroufe 1983, Dautenhahn 1995, Fong et al. 2003 and Marin et al. 2009). In order to increase the social competence of a robot and consequently engage itself more effectively in the interaction with a human, it is important to investigate people's attitudes towards robots and how they perceive robots.

The core research objective of my PhD work is the development and investigation of a method, endowed with which, the social competence of a humanoid robot can be enhanced by adapting its behaviours to a human in real-time interaction. As part of this study, I also investigated the phenomenon of motor interference, which may help to reveal human beings' subconscious preference of a robot and which factors of a robot may influence the perception of a human to this robot.

Please note that, in this dissertation, the broader term behaviour adaptation is used to refer to studies on motor coordination and immediate imitation.

1.1 Motivation

This study is motivated by the idea that human-humanoid interactions may be facilitated and evaluated by drawing inspirations from human-human interactions because humanoid robots can be considered as anthropomorphic agents.

Robots have been widely used in various areas, such as industry, domestic service, search and rescue, space exploration, therapeutic aids, education and research. All these robot applications have certain forms of interactions between themselves and human beings although some of them are regarded as "fully autonomous" because they are eventually used by and working for humans. Therefore, Human-Robot Interaction (HRI), as a research field motivated by the intention to "*understand and shape the interactions between one or more humans and one or more robots*", has attracted increasing attention from researchers (Goodrich and Schultz 2007).

One major aim of HRI research is to enable a human to interact with a robot in a 'natural' manner (Dautenhahn 2007). An underlying assumption related to this aim is that people prefer to retain the way that they interact with other people when they interact with robots (Fong et al. 2002, 2003). Numerous studies have been performed to investigate how to make robots operate as partners or companions that can be comfortably accepted by humans (Adams and Skubic 2005, Dautenhahn 2007, and Goodrich and Schultz 2007). One direction is to draw inspirations from human-human interactions and then apply them in Human-Robot Interactions (Huber et al. 2008). Recent research depicted a framework, motor resonance, which was described as "*the influence the perception of another individual's action has on the execution of actions by the self* (Marin et al. 2009)". This framework was proposed for understanding human-human interactions. Nevertheless, it can also be applied to interactions between humans and humanoid robots due to the anthropomorphic features of the robot (Marin et al. 2009). Motor coordination and motor interference, as two behaviours derived from this framework, have been widely studied.

Motor coordination is a phenomenon that can be experienced consciously and unconsciously (Schmidt and Richardson 2008), and can be regarded as "*a behavioural manifestation of social rapport, or that mimicry reflects a relational or other-directed focus*" (Richardson et al. 2005). Motor coordination has been suggested to be a desirable and positively evaluated characteristic of interactions (Hubbard 2000). For example, you may often find people synchronize their leg movements with others when they are walking side-by-side (Van Ulzen et al. 2008). It has been suggested that by means of introducing motor coordination features in robots' behaviours, robots may be able to interact with humans in a more natural form and eventually improve the quality of Human-Robot Interaction (Marin et al. 2009).

Motor interference (also referred to as the *interference effect*), can be understood as the interference between observation and execution of action in the face-to-face interaction of two agents (Chaminade et al. 2005). Motor interference is thought to be generated by co-activation of conflicting populations of mirror neurons and emerges when an agent is observing and performing incongruent movements (Kilner et al. 2003). The mirror neurons were discovered in the premotor cortex of macaque monkeys, which are thought to be in charge of matching observation and execution of motor actions (Gallese et al. 1996, Rizzolatti et al. 1996). The interference effect can be commonly observed in human-human interactions (Oztop et al. 2005, Stanley et al. 2007). In Human-Robot Interactions, the study performed by Kilner et al. (Kilner et al. 2003) found no interference effect when a human was interacting with a mechanical robot arm. However, some researchers found that the interference effect could be still elicited if a robot had a certain level of 'human-like' features, such as human-like appearance and biological motion profile (Oztop et al. 2005, Chaminade et al. 2005 and Kupferberg et al. 2009). Nevertheless, other studies suggested that motor interference could be found with neither human-like appearance nor biological motion features (Stanley et al. 2007, Bouquet et al. 2007 and Kilner et al. 2007). Instead, the work conducted by Stanley et al. (Stanley et al. 2007) suggested that the top-down effects of agency belief might be critical to elicit motor interference. It has therefore been suggested that motor interference can be used to evaluate the quality of Human-Robot Interaction (Oztop et al. 2005, Marin et al. 2009). Thus the investigation of possible features in human-humanoid interactions that might cause the interference effect can potentially help to facilitate human-humanoid interactions.

1.2 Research Questions

The central thesis of this work is to demonstrate how an embodied humanoid robot with motor coordination capability inspired from human-human interactions can be realized to facilitate human-humanoid interactions. The secondary aim of this study is to present how motor interference can be used to evaluate the quality of human-humanoid interactions and investigate which feature in human-humanoid interactions may elicit motor interference.

In order to achieve these goals, a real-time synchrony detection method is required, which enables a robot to inspect how well its own movements are synchronized with a human's movements. If its own movements and the human's movements are out of synchronization, the robot can learn this information from its internal status and coordinate its movements to the human's movements. Therefore, the first research question of this thesis is:

1. Can a method be developed that can be used in real time to detect synchrony in Human-Humanoid Interaction?

A set of experimental studies need to be performed to investigate the impact of motor coordination and the elicitation of motor interference in human-humanoid interactions. An investigation of this research area indicated that the interference effect was only present when a human was interacting with a humanoid robot with biological motion profile (Oztop et al. 2005). However, another study found that the interference effect could be elicited using a virtual moving dot without biological motion profile (Stanley et al. 2007). Therefore, in the studies reported in this thesis, a humanoid robot without biological motion profile was used to test whether this robot could elicit the interference effect in human-humanoid interaction. In these studies I have placed emphasis on keeping human-humanoid interactions ‘natural’ and have ensured that the experimental scenarios proposed are playful. This differs from other work in this area where the experimental studies tend to engage human actions in a relatively unnatural setting (Oztop et al. 2005). Hence, the research question related to the first experiment is:

2. A) Can an interference effect be found in a playful Human-Robot Interaction experiment using a social robot that does not behave according to a biological motion profile?
   B) Can a human’s motor coordination be elicited using the same social robot and the same experimental setup as in 2. A)?

As the appearance of the face and body of the humanoid robot used in this experiment looks more human-like than the robot used in Oztop et al.’s work (more details are provided in Chapter 4), it was hypothesized that if the facial and body appearance of a robot is the critical factor to elicit motor interference, a significant interference effect may be found. Previous research by Robins et al. (Robins et al. 2008) suggested that children may adapt the timing of their movements to an embodied humanoid robot’s movements. Therefore, it was hypothesized that the human participants in this experiment may also coordinate their movements to the robot’s movements.

In the second experiment, both motor interference and motor coordination are further investigated by comparing the responses of human participants when they are interacting with a humanoid robot, a mechanical pendulum and a virtual moving dot. In addition, for the motor interference part, the impact of a human’s belief to the elicitation of motor interference is investigated. The research question of the second experiment is:

3. A) Can a human's belief have an impact on producing an interference effect when interacting with the same robot mentioned in question 2?
   B) Can a social robot elicit a human's motor coordination compared with a virtual moving dot or a mechanical pendulum?

Based on the results of Stanley et al.'s work (Stanley et al. 2007), which suggested that the top-down effects of agency belief might be critical to elicit motor interference, it was hypothesized that a human's belief in human-humanoid interactions may facilitate the elicitation of the interference effect.

The third experiment is carried out to validate the motor coordination competency of a humanoid robot, which uses the information distance method to measure behaviour synchrony, and evaluate the quality of interactions between a human and a humanoid robot, with or without motor coordination capability. It was hypothesized that human participants may prefer to interact with a robot with motor coordination competency. The research question for the final experiment is:

4. A) Can the synchrony detection method be developed and used in real-time to help a social robot to adapt its behaviour to a human's behaviour?
   B) Will a human prefer a social robot that adapts to his/ her behaviour compared to a social robot that does not adapt to his/her behaviour?

1.3 Contributions to Knowledge

The main contributions of this thesis are listed as follows:

1. Introduce a novel method to measure synchrony between two agents' behaviours using information distance (Crutchfield 1990). The performance of this method is validated in real-time interactions between a human and an embodied humanoid robot, which generates small information distance values as indications of synchronous behaviours and large information distance values as indications of asynchronous behaviours.

2. Through the experimental investigations of motor interference conducted in this study, it is found that human observers' overall perception of a robot as a 'social entity' (in this study, the term 'overall perception' refers to the human observers' overall perceptions of a robot in terms of appearance, motion, observers' beliefs and environmental features as related to a 'social entity') instead of any individual appearance or motion feature may possibly be the factor that is critical to elicit the interference effect in human-humanoid interaction.

3. A set of experimental investigations for motor coordination is performed, through which the responses of human participants to different visual stimuli are investigated. The results indicate that the participants prefer to coordinate their movements to the agent with the best 'overall perception' as a social entity.

4. A new experimental scenario is proposed, in which motor coordination between a human and a humanoid robot can be realized with the information distance method as the synchrony measure.

5. An experiment is performed using the proposed experimental scenario about motor coordination. The experiment results validate the design of the scenario. Furthermore, the survey feedback from the participants indicates that the participants prefer to interact with a humanoid robot with motor coordination capability than with a humanoid robot without this capability.

1.4 Overview of the Thesis

Chapter 2 provides an introduction and literature review of issues about Human-Robot Interactions, including inspiration drawn from Human-Human Interactions, the motor resonance framework, motor interference, motor coordination and immediate imitation.

Chapter 3 describes the developmental process of the information distance method. Starting with a brief introduction to information theory and information distance, followed by the construction of the information distance method and the validation process.

Chapter 4 presents two experimental investigations concerning motor interference and motor coordination in Human-Humanoid Interactions. In both experiments, participants are instructed to interact with a humanoid robot. Factors that may influence motor interference and motor coordination, such as music, different arm movement directions and participants’ beliefs, are introduced in the two experiments respectively. In the second experiment, the participants are required to interact with a mechanical pendulum and a virtual moving dot as well as the humanoid robot. The experiment results of both experiments are presented and the differences between these two experiments are discussed.

Chapter 5 describes an experiment, in which human participants are instructed to interact with a humanoid robot that tries to coordinate its movements with human participants' movements by adopting the information distance synchrony measure. The experiment results are presented and discussed.

Chapter 6 summarizes all the findings in the experiments and discusses their implications. A review of the issues related to the research questions and contributions to knowledge is presented.

Chapter 7 concludes the thesis and outlines the future directions, possible applications and future experimental studies.

Chapter 2
Background

The main research focus of this work is motor interference and motor coordination in human-humanoid interaction. In this chapter, the research background and the motivation of this thesis is presented and examined. The chapter starts with an introduction of the research background of this thesis, beginning from human-robot interaction and then more specifically going into human-humanoid interaction. Afterwards, recent research concerning motor interference and motor coordination, as the two behaviours derived from the motor resonance framework, in human-human interaction and human-robot interaction are critically reviewed and discussed. At the end of the chapter, the research questions are revised according to the critical review.

A more detailed description of each section is given below: in section 2.1, a number of studies are illustrated at the beginning to depict a brief outline of the human-robot interaction research area. The section then focusses on the issues related to social interaction between humans and robots. One of the issues is the appearance issue of social robots, which is a major difference between humanoid robots and other social robots. The other issue is about human-humanoid interaction. A brief review of what has motivated the development of human-humanoid interaction research is presented. Section 2.2 examines the possible inspirations from human-human interaction to human-robot interaction, starting from the motor resonance framework to three important behaviours that are associated with this framework: motor interference, motor coordination and immediate imitation. In section 2.3, recent studies concerning motor interference in interactions between humans and various types of agents, including other humans, mechanical robots, humanoid robots and moving dots, are critically reviewed to evaluate the impact of different factors on the elicitation of the interference effects. In Section 2.4, several studies related to motor coordination in human-robot interaction are reviewed to propose a primary attempt of realizing the motor coordination mechanism on a humanoid robot. The synchrony measurement method included in this mechanism is also discussed. In section 2.5, the research questions associated with the previous review are listed and revised. Finally, the conclusion of this chapter is given in section 2.6.

2.1 Human-Robot Interaction

With the development of robot technology from the last century, Human-Robot Interaction has attracted increasing attention from researchers from various subjects, such as psychology, cognitive science, social science, engineering, computer science, artificial intelligence and robotics. According to Goodrich and Schultz's study (Goodrich and Schultz 2007), there are two general types of human-robot interaction, *remote interaction* and *proximate interaction*. For remote interaction, the humans and the robots are usually separate spatially or even temporally. For proximate interaction, the humans and the robots are normally co-located.

Remote interaction between humans and robots can be found in applications such as police Special Weapons and Tactics (SWAT) and Urban Search and Rescue (USAR) (Murphy 2004 and Green et al. 2008). For example, Jones et al.'s study (Jones et al. 2002) explored the utilization of an autonomous robot by a SWAT team in a SWAT environment (illustrated in Figure 2.1a). Their findings suggested that a robot with predictable mobility, onboard sensing ability, an efficient data gathering system as well as ease with directing was the most ideal choice for a SWAT team.

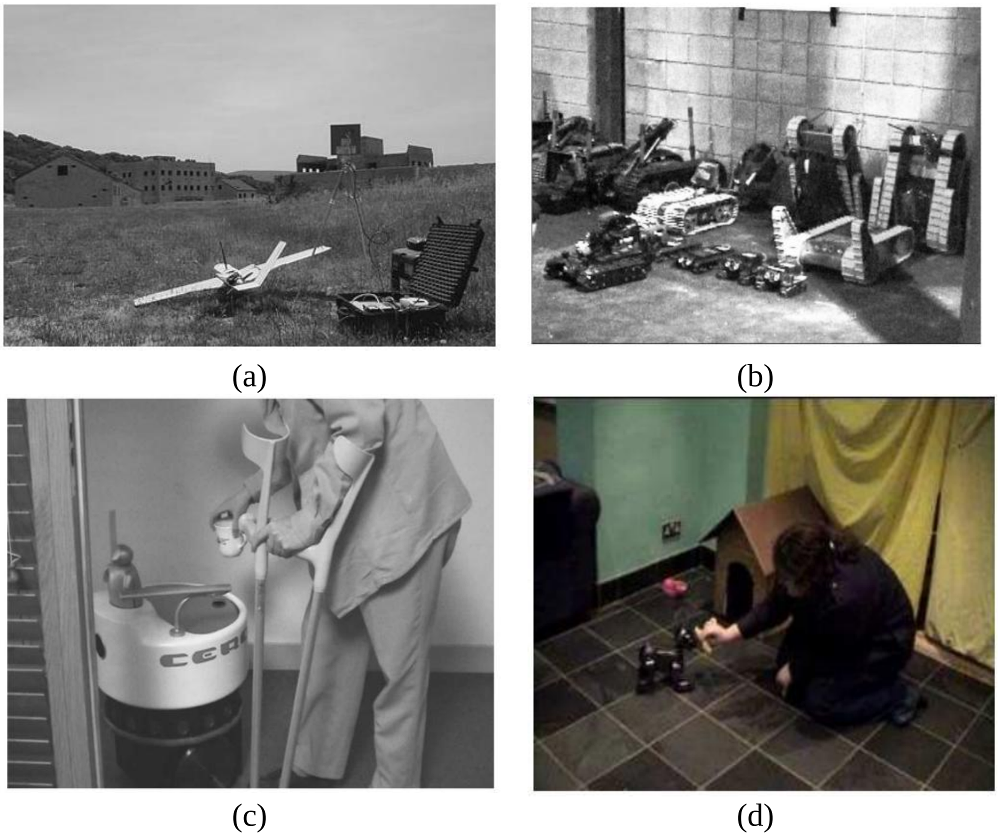


Figure 2.1: illustrates different type of human-robot interaction in various applications: (a) The MLB Bat, which is an autonomous Unmanned Aerial Vehicle (UAV) system, can operate autonomously and delivers high quality real-time video imagery and sensor data (this figure is sourced from Jones et al. 2002); (b) illustrates examples of USAR robots brought to WTC response (this figure is sourced from Murphy 2004); (c) a user is loading the service robot, Cero (this figure is sourced from Hüttenrauch et al. 2004); (d) A child and an Aibo robot are responding to each other ((this figure is sourced from Robins et al. 2005).

Casper and Murphy’s work (Casper 2002, Casper and Murphy 2003) investigated the human-robot interaction in the application of rescue robots in the World Trade Center disaster incident (illustrated in Figure 2.1b). They made a number of suggestions concerning how the human-robot interaction in the USAR area could be improved in various aspects, including reliability, sensor system, localization, user interface, professional training, user confidence, transportation and operation ratio, etc.

Proximate interaction with robots is often seen in the interactions between humans and robots where the robots are used as assistants or companions. For instance, Hüttenrauch and colleagues developed a service robot, Cero (illustrated in Figure 2.1c), which assisted people in an office environment (Hüttenrauch et al. 2004). The evaluation results of the usage of Cero indicated that long-term testing with users in real-life was very important for service robot design. In addition, their results also suggested that a service robot should be designed to interact with multiple users instead of an individual user. Robins et al.'s study used a robot dog to investigate how a robot pet could preserve the interaction dynamics and engagement with a child (Robins et al. 2005). The experimental results of their study indicated that the factors such as the context of interaction, showing attention by the robot, turn taking, appropriate timing and rhythm had very important impact on regulating human-robot interaction (the interaction between a child and a robot dog is illustrated in Figure 2.1d).

The interaction between the children and the robot dog in Robins et al.'s study is a typical example of social interaction, in which humans and robots interact as peers or partners. This type of interaction between humans and robots generally happens proximately instead of remotely (Goodrich and Schultz 2007). A robot endowed with social behaviours, such as the robot dog in Robins et al.'s work, can be regarded as a social robot. A more specific definition of social robot was proposed by Dautenhahn and Billard: "*Social robots are embodied agents that are part of a heterogeneous group: a society of robots or humans. They are able to recognize each other and engage in social interactions, they possess histories (perceive and interpret* *the world in terms of their own experience), and they explicitly communicate with and learn from each other*" (Fong et al. 2003 and Dautenhahn and Billard 1999).

Interaction with social robots has recently become a main research direction of human-robot interaction (Breazeal and Scassellati 1999, Breazeal 2003, Dautenhahn 1998, Dautenhahn et al. 2006, Nakauchi and Simmons 2000, Restivo 2001, Sabanovic et al. 2007, Severinson-Eklund et al. 2003 and Syrdal et al. 2007a). One of the major aims of developing social robots is to enable humans to interact with robots in a natural manner and consequently improve the quality of human-robot interaction (please refer to Fong et al. 2002, 2003 for a detailed review of socially interactive robots). In this section, a couple of issues in the social robotics domain, the appearance design of social robots and the motivation of the development of human-humanoid interaction, are presented.

2.1.1 Robot Appearance

The appearance of robots plays an important role in human-robot interaction. When a human is interacting with an embodied robot, it is very likely that the human gets the first impression of the robot from its appearance. It has been validated in many studies that the appearance of a robot may have significant impact on the perception of a human to this robot (DiSalvo et al. 2002, Robins et al. 2004a, Syrdal et al. 2007b and Woods et al. 2005). The possible underlying reason may be rather straightforward: we behave in a similar way in human-human interactions. Alicke et al.'s study indicated that the appearance of humans, such as faces and bodies, significantly influenced other people's judgement of their physical attractiveness (Alicke et al. 1986). Therefore, a robot with an appropriate appearance may significantly increase its social competence.

Anthropomorphism

To improve a robot's appearance for social interaction with humans, adding human-like features is a commonly used approach, which has been suggested as being able to facilitate a human's social understanding (Duffy et al. 2002). This tendency to attribute human characteristics to agents with a view to helping rationalize their actions is referred as *Anthropomorphism*, which acts as a mechanism to fine-tune the interaction between a social robot and a human (Duffy 2003, Fong et al. 2003).

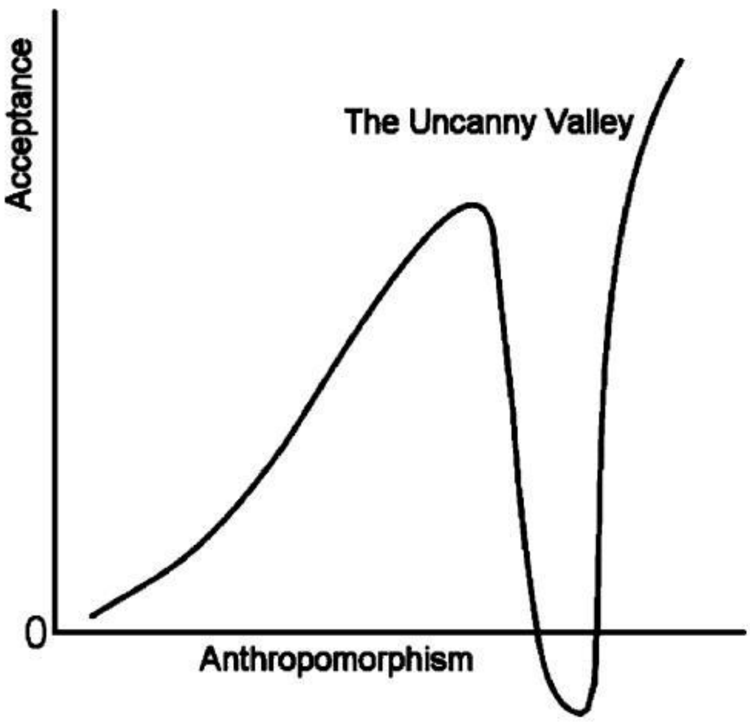


Figure 2.2: illustrates Mori's "the uncanny valley" hypothesis (this figure is sourced from Duffy 2003).

It has also been suggested that humans tend to build their initial expectation of a robot's function based on the robot's appearance (Goetz et al. 2003 and Hinds et al. 2004). If the matching between the appearance of the robot and its function fulfils humans' expectation, it may systematically increase their willingness to interact with that robot (Goetz et al. 2003). On the other hand, unconstrained anthropomorphism may cause humans to develop false expectation to the robot's function and consequently result in negative impact on interaction with the robot (Duffy 2003). The uncanny valley hypothesis, proposed by Masahiro Mori (Mori 1970), illustrated this issue nicely.

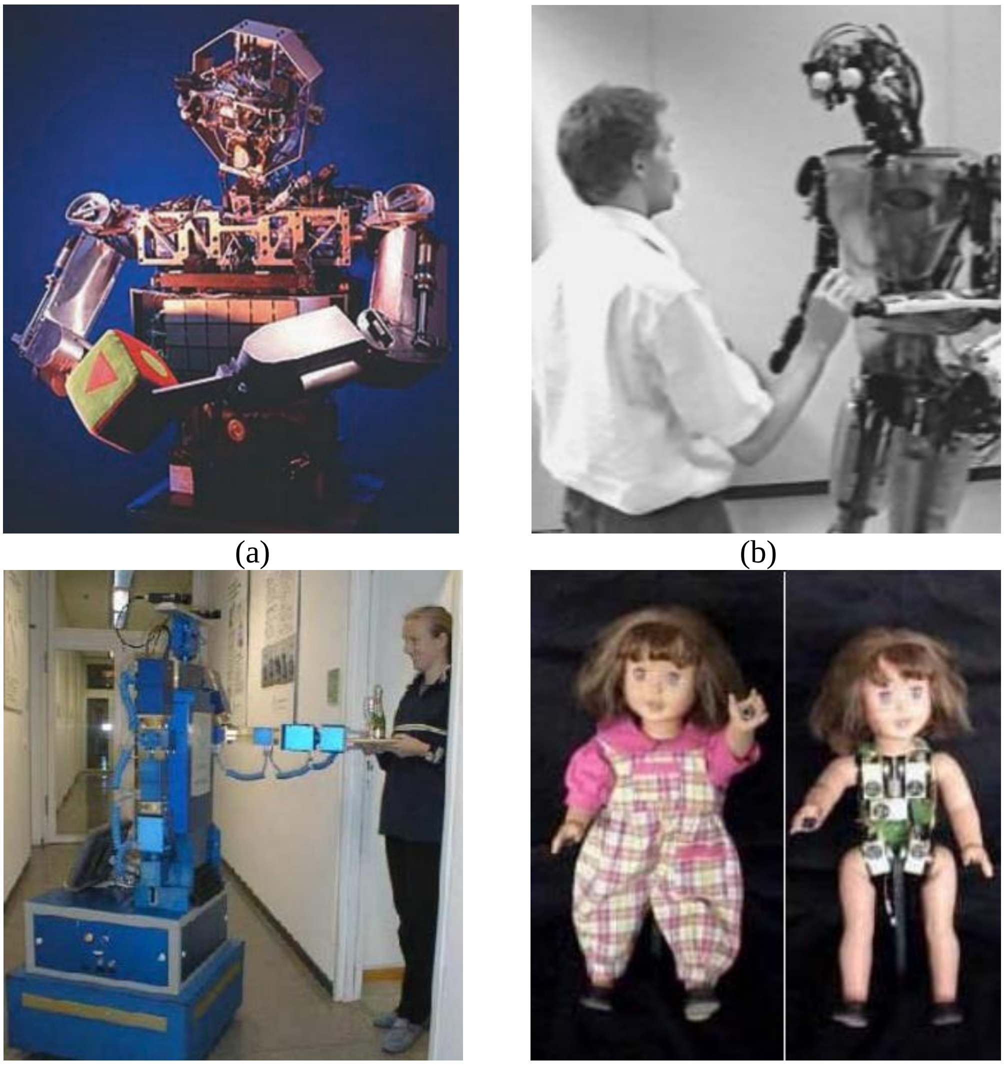
Mori suggested that humans' sense of a robot's familiarity increased when the robot exhibited more human-like features. However, at a certain point, the robot might induce repulsive reactions in humans due to its imperfect human-likeness (illustrated in Figure 2.2). Woods et al.'s work (Woods et al. 2004) found that children preferred human-machine like robots over human-like robots supported the uncanny valley hypothesis (the children judged human-like robots as aggressive but human-machine like robots as friendly). Therefore, we should be aware that the application of anthropomorphic qualities in designing a robot's appearance needs to maintain an appropriate balance between "human-ness" and "robot-ness" to support its human-like interaction with people (Duffy 2003, Fong et al. 2003).

2.1.2 Human-Humanoid Interaction

Humanoid robots, as a class of artificial anthropomorphic agents, may naturally induce responses from other humans in a human-human interaction manner through appropriate exploitation of their human-like features (Cheng et al. 2001). Walters et al.'s study (Walters et al. 2008) gave a definition of a humanoid robot based on Gong and Nass's work (Gong and Nass 2007): "*a robot which is not realistically human-like in appearance and is readily perceived as a robot by human interactants. However, it will* *possess some human-like features, which are usually stylized, simplified or cartoon-like versions of the human equivalents, including some or all of the following: a head, facial features, eyes, ears, eyebrows, arms, hands, legs. It may have wheels for locomotion or use legs for walking*."

One main motivation for developing humanoid robots is to explore the underlying theory and mechanism of human behaviours and human intelligence. Many researches possess a similar idea as suggested by Atkeson and colleagues (Atkeson et al. 2000), "*our understanding of human behaviour advances as our human robotics work progresses – and vice versa*". By programming a humanoid robot to perform certain movements may help researchers to understand how human brains operate to control human body parts to perform similar movements. On the other hand, a better understanding of how human behaviours have emerged can help researchers to duplicate similar mechanisms on a humanoid robot to generate human-like behaviours. A humanoid robot equipped with more human-like behaviours may result in more natural interaction with humans and consequently interact with people in a better way.

Numerous humanoid robot platforms and functionalities that support social interaction with humans have been developed to achieve the above aims. Adams and colleagues developed a humanoid robot, Cog (illustrated in Figure 2.3a), which could be used as a tool to evaluate and test models drawn from cognitive science and behavioural science (Adams et al. 2000). Scassellati (Scassellati 2000), for example, used this humanoid robot to implement joint attention behaviours that followed the eye gaze of others to share attention. Hale and Pollick adopted another humanoid robot platform, DB (illustrated in Figure 2.3b), to develop the robot's own motion from learning and generalizing the observed motion from interaction with a human in a physical contact game called "Sticky Hands" (Hale and Pollick 2005).



(a) (b) (c) (d)

Figure 2.3: illustrates several humanoid robots used in various applications: (a) a humanoid robot platform, Cog, was developed to emulate human movement as closely as possible (this figure is sourced from Adams et al. 2000);(b) a humanoid robot, DB, playing Sticky Hands with a human (this figure is sourced from Hale and Pollick 2005) (c) a humanoid service robot, HERMES, receiving a tray from a human (this figure is sourced from Bischoff 1999); (d) a humanoid robotic doll, Robota, used to interact with children with autism (this figure is sourced from Robins et al. 2004);

There are also some humanoid robots particularly developed as service robots. For instance, Bischoff (Bischoff 1999) described a humanoid service robot, HERMES (illustrated in Fgiure 2.3c), which was able to implement simple service tasks upon users' request, e.g. receiving a tray from a human and placing it on a table.

Moreover, humanoid robots can be applied as therapeutic and educational tools to help humans. Robins et al.'s work used a humanoid robot, Robota (illustrated in Figure 2.3d) in therapy and education of children with autism and found that the robot could encourage imitative and turn-taking games in interaction with these children (Robins et al. 2004).

Apart from those field studies illustrated above, the development and application of many other humanoid robots, such as the Honda humanoid robot P2 and P3 (Hirai et al. 1998), HRP-2W (Inamura et al. 2009), ARMAR (Asfour et al. 1999) and Robovie (Yamaoka et al. 2005), have also made great contributions to the development of human-humanoid interaction.

Despite the fact that a lot of work has been devoted to human-humanoid interaction and largely facilitates its development, there is still a long way to go for human-humanoid interaction to achieve an ideal level of naturalness as is currently only perceived in science fiction. It remains a challenge as to how the quality of human-robot interaction can be evaluated. How do humans perceive the humanoid robots they are interacting with? Whether they treat it as a peer or as a machine? Is there any way to reveal what humans really think apart from questionnaires? To answer these questions, inspirations from human social interaction may provide a valid approach.

2.2 Inspirations from Human Social Interactions

The biological-inspired approach is widely used to develop robots that simulate the social behaviours or intelligence of living creatures (Fong et al.

2003). Mechanisms that facilitate human social interaction may also be employed by a humanoid robot to improve human-humanoid interaction. In section 2.3, 2.4 and this section, the knowledge of motor resonance, a framework that is proposed to play a critical role in human social interactions (Marin et al. 2009), and several behaviours associated with this framework (namely, motor interference, motor coordination and immediate imitation) may be utilized in human-humanoid interaction is discussed. By understanding how these mechanisms and elements facilitate human-human social interaction, researchers may develop similar mechanisms and functions on humanoid robots to produce human-like behaviours, which may induce natural responses from humans.

2.2.1 The Motor Resonance Framework

It was hypothesised that human cognitive skills originate from human social interactions (Tomasello 1998). Motor resonance, which has been regarded as a basic mechanism of human social interaction, is thought to be the coupling between action and perception. This mechanism automatically actives the perceiver's motor control system during action perception (Chaminade and Hodgins 2006, Sciutti et al. 2012). That is, when a human is observing an action performed by others, motor resonance facilitates the production of the same action (referred to as motor priming) and inhibits the production of a different action (referred to as motor interference). This phenomenon may suggest that action perception and execution are not two entirely distinct processes (Oztop et al. 2005). Instead, these two processes may share a similar motor repertoire.

The neurophysiological basis of motor resonance is proposed to be the mirror neurons, which were initially found in the premotor cortex of macaque monkeys (Gallese et al. 1996, Rizzolatti et al. 1996). These mirror neurons discharge not only during a subject performing an action but also during the subject perceiving a similar action made by another agent (Gallese et al. 1996, Rizzolatti et al. 1996 and Keysers 2003). Researchers have also identified that similar regions in human brains are activated during action observation, which may validate the existence of the mirror neuron system in human brains (Hari et al. 1998, Blakemore and Frith 2005, Buccino et al. 2001). These studies support the hypothesis that the mirror neuron system is the substrate of the motor resonance mechanism.

As a mechanism that mediates action perception and action execution, motor resonance is involved in a large amount of social behaviours, including those automatic and subconscious processes like motor interference and motor coordination. Motor interference, as a behaviour derived from motor resonance, reflects humans' subconscious reactions to the observed stimuli (Brass et al. 2000, Kilner et al. 2003, Oztop et al. 2005). Motor priming, which is another behaviour derived from the motor resonance framework, is often used to explain behaviours such as motor coordination and immediate imitation. Both motor coordination and imitation behaviours have been proposed to occur because the observed action influences or facilitates the production of a same or similar action due to the strong link between action perception and production (Chartrand and Bargh 1999, Richardson et al. 2005, Sciutti et al. 2012). Further details on motor interference, motor coordination and immediate imitation are introduced in section 2.2.2, 2.2.3 and 2.2.4 respectively.

2.2.2 Motor Interference

A human subject's movements can be curbed when this subject is observing an incongruent movement produced by others. This phenomenon is an example of the elicitation of motor interference (also referred to as the interference effect), which can be explained by "*postulating that observing an action injects bias to the control affecting the performance by increasing the influence of modules controlling congruent movements, and decreasing the influence of modules controlling incongruent movements*" (Oztop et al. 2005).

An experiment conducted by Brass and colleagues demonstrated the presence of the interference effect (Brass et al. 2000). In their experiment, participants were instructed to use their index finger or middle finger to respond to visual stimuli presented in a video recording. The visual stimuli consisted of congruent or incongruent human finger movements and congruent or incongruent symbolic cues. The experimental results showed that observing incongruent finger movements significantly increased the participants' reaction time and observing congruent finger movements significantly reduced the reaction time. However, the results suggested that the symbolic cue did not influence the reaction time of the participants' finger movements. These experimental results were generally in-line with the motor resonance framework: observing and performing congruent movements facilitated the movement performance while observing and performing incongruent movements hindered the movement performance.

The results of Brass et al.'s study also reflected the participants' subconscious preference to the visual stimuli. The human finger movement video elicited a strong interference effect in the participants' movements. In stark contrast, the symbolic cue (Arabic numbers) had no influence on the participants' behaviours. The large difference between the participants' subconscious reactions to these two stimuli might imply that the visual stimuli had to have enough anthropomorphic features to successfully elicit the interference effect. If this is the case, the human's subconscious reaction to visual stimuli may provide a potential approach to investigate how humans perceive artificial agents such as humanoid robots. This assumption has been supported by many studies (Oztop et al. 2005, Marin et al. 2009 and Sciutti et al. 2012). For more details please refer to section 2.3.

2.2.3 Motor Coordination

It has been suggested by past psychological research that socially situated agents tend to coordinate their motor behaviours (Schmidt and Richardson 2008). According to Bernieri and Rosenthal's work (Bernieri and Rosenthal 1991), there are two types of motor coordination: one called *behaviour matching* and the other called *interactional synchrony*. Please note that the term behaviour matching used in Bernieri and Rosenthal's study often refers to mimicry (Richardson et al. 2005). Both types of interpersonal motor coordination can be commonly observed in our everyday life.

A typical example for behaviour matching is the chameleon effect, which has been proposed to be represented as "*nonconscious mimicry of the postures, mannerisms, facial expressions, and other behaviours of one's interaction partners, such that one's behaviour passively and unintentionally changes to match that of others in one's current social environment*" (Chartrand and Bargh 1999). In Chartrand and Bargh's experiments, the results validated the existence of the chameleon effect by finding that the participants subconsciously changed their behaviours according the changes in their confederates' behaviours. In addition, their experimental results suggested that non-conscious mimicry facilitated smooth interactions and increased rapport (or liking) between interaction companions.

Automatic synchronization of walking partners' leg movements when they are walking side-by-side can be an instance of interpersonal synchrony (Van Ulzen et al. 2008). The findings of Van Ulzen et al.'s study indicated that the participants' leg movements were entrained during walking in pairs regardless of whether the participants were particularly instructed to coordinate their leg movements. Thus, interpersonal synchrony was validated in both conscious and unconscious conditions in Van Ulzen et al.'s experiment.

Similar to the findings in Chartrand and Bargh's work (Chartrand and Bargh 1999), Wiltermuth and Heath's study (Wiltermuth and Heath 2009) found that interpersonal synchrony could also benefit the establishment of rapport. The experimental results of their study suggested that synchronous activity could promote cooperation among group members. Therefore, it has been found that both types of motor coordination behaviour are able to increase rapport (or liking) among interaction partners. In addition, Lakin and Chartrand's study (Lakin and Chartrand 2003) indicated that the desire to create rapport with confederates, in turn, increased individuals' non-conscious mimicry.

All these studies might demonstrate that the interplay between motor coordination behaviours and rapport was positively related as suggested by LaFrance's study (LaFrance 1979). It might also exhibit the mutual understanding of the adoption of motor coordination behaviour among interaction partners, although none of them was aware of this process. To summarize, motor coordination is a kind of dynamical process that may increase rapport or liking between interaction partners and therefore facilitate interpersonal interaction.

2.2.4 Immediate Imitation

Immediate imitation is a primary ability of humans. It offers an approach for young children to acquire referential communication skills, starting from developing selective matching movements from the human repertoire to constructing shared topics with a co-referent (Nadel et al. 1999). The imitation behaviour, at the lowest level, is regarded as a special case of translation from sensory input into motor action (Wohlschlaeger et al. 2003), which demonstrates the link between perception and action (Sciutti et al. 2012).

In this thesis, the term immediate imitation particularly refers to a mechanism that mediates action perception and the corresponding action production. This mechanism is implemented on a humanoid robot to act as a primary simulation of the perception-behaviour link. It directly maps the observed action of an agent onto the robot's own motor system with an explicit mapping strategy to address the correspondence problem (Nehaniv and Dautenhahn 2002). The details of the actual implementation please refer to section 3.4.2.

The implementation of the immediate imitation mechanism provides a superficial validation of the perception-behaviour link on an embodied humanoid robot. It also grounds the basis for realizing more complex social behaviours in future research.

2.3 Motor Interference and Human-Humanoid Interaction

To understand how humans perceive a robot is one of the key issues in human-robot interaction. If the perception of a robot matches the preference of a human, the interaction between the human and the robot may be largely facilitated. Various approaches have been attempted to investigate this issue. Many studies such as DiSalvo et al.'s study (DiSalvo et al. 2002) and Bartneck et al.'s study (Bartneck et al. 2009) adopted questionnaires to investigate users' perception of robots. However, it has been suggested that sole usage of questionnaires only accesses humans' conscious evaluations of robots but does not take the unconscious reactions to the robots into consideration (Sciutti et al. 2012).

Therefore, other measurements are required in order to fully quantify human-robot interaction. Some physiological measurements, such as galvanic skin conductance, muscle and ocular activities (Dehais et al. 2011), EEG signals (Wada et al. 2005), and heart rate (Rani et al. 2002), have been used to depict humans' subconscious responses to robots (Sciutti et al. 2012).

In addition, motor interference, derived from motor resonance, provides an option to measure human's subconscious perception of a robot from a perspective closely related to human-robot social interaction. If a humanoid robot could successfully elicit the interference effect in its interaction with humans, it may imply that the humans subconsciously treat this robot as an interaction partner or a companion.

In this section, recent studies investigating motor interference in interpersonal interaction and interactions between humans and artificial stimuli are critically reviewed respectively.

2.3.1 Motor Interference in Human-Human Interactions

In section 2.2.2, an experiment performed by Brass et al. (Brass et al. 2000) concerning motor interference was illustrated. In that experiment, the human participants were observing video recordings of human finger movements instead of a real human. Recently, Kilner and colleagues conducted an experiment to investigate the elicitation of the interference effect in both human-human interaction and human-robot interaction (Kilner et al. 2003). In their experiment, the interference effect was found when the participants were instructed to perform horizontal or vertical arm movements while observing either a human experimenter or a mechanical robot performing congruent or incongruent arm movements. The results implied that the interference effect was only present in human-human interaction but absent in the human-robot interaction. Please note that the movements performed by the mechanical robot did not adopt a biological motion profile and that robot might not have a human-like appearance. The examples of the presence and the absence of the interference effect when a human is performing arm waving movements when observing another agent performing congruent or incongruent arm waving movements are illustrated in table 2.1.

Table 2.1: this table illustrates the arm movement direction executed and observed by a human under the condition when the interference effect is present and when the interference effect is absent: When the human is performing horizontal waving movements while observing another agent also performing horizontal waving movements (congruent condition), the interference effect is not present. However, when the human is performing horizontal waving movements while observing another agent performing vertical waving movements, the interference effect may appear (incongruent condition). In this example, the interference effect is represented by significant increase of a human's movement variances that is orthogonal to the human's main movement direction.

Agent	**Interference Absent**		**Interference Present**	
Human	Horizontal	Vertical	Horizontal	Vertical
				
Observed Agent	Horizontal	Vertical	Vertical	Horizontal
				

The experimental results of Kilner et al.'s study (Kilner et al. 2003) concerning human-human interaction have been validated by Oztop et al.'s study (Oztop et al. 2005), Stanley et al.'s study (Stanley et al. 2007) and Bouquet et al.'s study (Bouquet et al. 2007). In these studies, observing human experimenters performing incongruent arm movements could induce a significant increase of movement variances in the participants' arm movements. Moreover, the studies by Bouquet et al. (Bouquet et al. 2007) and Kupferberg et al. (Kupferberg et al. 2009, Kupferberg et al. 2011) together with Brass et al.'s study (Brass et al. 2000) illustrated above demonstrated that observing the video recording of a human experimenter's movements could achieve an equivalent effect as that of observing a real human performing the same movements.

In the above studies, human performers were not explicitly instructed to perform their movements in a non-biological manner. Therefore, it could be assumed that the human performers should have performed their movements in a way that they are used to, i.e. in a biological manner. Nevertheless, it was reported that when the participants were observing a video of a human performer performing incongruent arm movements in a non-biological manner, the interference effect became absent (Kilner et al. 2007). This part of the results of Kilner et al.'s study will be further discussed in section 2.3.2 together with the rest of the results of the same study.

2.3.2 Motor Interference in Interactions between Human and Other Agents

It has been a debate for a period of time what critical factor enables an artificial visual stimulus to elicit the interference effect in a human observer's movements. In Kilner et al.'s initial experiment (Kilner et al.

2003), no interference effect was found when the human participants were observing arm movements performed by a mechanical robot. The study carried out by Oztop et al. (Oztop et al. 2005) successfully found the interference effect in human-humanoid interaction. Their experimental results suggested that a robot possessing more anthropomorphic features, such as human-like appearance and movements with a biological motion profile could provoke the interference effect. Oztop et al.'s findings were supported by Press et al.'s work investigating motor priming (Press et al. 2005, Press et al. 2006), which has been proposed as an effect comparable to motor interference and is also sourced from the motor resonance framework (Sciutti et al. 2012). It was suggested by Press and colleagues that the bottom-up visual properties of the stimuli may affect the elicitation of motor priming.

Chaminade et al.'s study (Chaminade et al. 2005) further proposed that the motion profile played a critical role in eliciting the interference effect. In their experiments, the interference effect was only significant when the movements of the robot adopted a biological motion profile. These results were supported by Kupferberg et al.'s experiment (Kupferberg et al. 2009, Kupferberg et al. 2011) that a humanoid robot with biological instead of non-biological motion features might provoke the interference effect. The conclusions drawn from these two studies were in-line with the finding of Kilner et al.'s experiment (Kilner et al. 2007) illustrated in section 2.3.1.

However, within the same study, the results of another experiment performed by Kilner et al. (Kilner et al. 2007) indicated that the videos of a moving ball stimulus interfered with the arm movements of the participants using both biological and non-biological incongruent movements. Those results demonstrated that the interference effect could be elicited by visual stimuli with neither human-like appearance nor biological motion features. Bouquet et al.'s study (Bouquet et al. 2007) supported Kilner et al.'s findings concerning the 'moving ball' videos. In their experiment, the interference effects were elicited when participants were observing incongruent motion produced by a moving dot for both biological and non-biological conditions. A possible explanation was proposed by Kilner et al. to interpret the different effects on observers' movements between observing a human and observing a moving ball. They speculated whether the interference effect could be elicited in a human's movements was largely associated to the human's prior experience of the observed stimuli and their motion. That is, if the observers were familiar with the observed stimuli and their motion profiles, the interference effect could be successfully elicited. Otherwise, the interference effect might be found absent.

2.3.3 The Impact of Human's Belief

A set of experiments performed by Stanley et al. (Stanley et al. 2007) found that the human participants' belief might play an important role in eliciting motor interference. In their experiments, they adopted two kinds of moving dot stimuli, one with a biological motion profile and the other with a non-biological profile. In each experimental trial, participants were asked to observe either of the moving dot stimuli when they were waving their arms. In the first experiment, participants were not given specific instructions about the origin of the moving dot stimuli. The experimental results suggested that the interference effects were apparent for both biological and non-biological moving dot stimuli. This part of the results was consistent with the findings of Bouquet et al and Kilner et al.'s study (Bouquet et al. 2007, Kilner et al. 2007) described in section 2.3.2.

In the second experiment of Stanley et al.'s work, half of the participants were told that the moving dot stimuli they observed were produced by a human (human-agent instruction group) and the other half were told that the moving dot stimuli they observed were generated by a computer (computer-agent instruction group) although all participants were observing exactly the same stimuli (both with a biological motion profile and a non-biological motion profile). The interference effects were found for the human-agent instruction group across both the biological motion profile condition and the non-biological motion profile condition and neither the biological motion profile condition nor the non-biological motion profile condition for the computer-agent instruction group elicited a significant interference effect. These results indicated that the top-down effects of agency belief might have critical influence on the presence of the interference effect.

The findings of Stanley et al.'s study (Stanley et al. 2007) seems to conflict with the bottom-up hypothesis proposed by Press et al.'s studies (Press et al. 2005, Press et al. 2006). However, compared with the visual stimuli used in Press et al.'s work (a human hand and a robotic hand), the differences between visual stimuli (a moving dot with biological motion profile and a moving dot with non-biological motion profile) used in Stanley et al.'s experiment were more ambiguous, which might explain the differences between the outcome of these two studies. It was noticeable that the interference effects for biological motion appeared to be more robust than non-biological motion in the first experiment of Stanley et al.'s work, which was in-line with the bottom-up hypothesis suggested by Press et al.'s work.

Although the conclusion drawn from Stanley et al.'s work might not fully explain all the experimental results of the studies illustrated previously, it provided an intriguing investigation perspective of the emergence of the interference effect. In this thesis, an experiment is presented to investigate whether human participant's belief could elicit the interference effect in human-humanoid interaction.

One point worth mentioning is that the interference effect is often represented by the significant increase of a human's movement variances and different studies might use different approaches to measure the movement variances. In many studies, such as Kilner et al. 2003, Stanley et al. 2007, Bouquet et al. 2007, Kilner et al. 2007 and Kupferberg et al. 2009, the human participants were instructed to wave their arms either horizontally or vertically and then the movement variances that were orthogonal to the main motion plane were measured to judge the presence of the interference effects. Oztop et al.'s study (Oztop et al. 2005), however, took an alternative approach by instructing the participants to wave diagonally (either from top-left to bottom-right or from top-right to bottom-left) and by measuring the variance of the movement lengths, and both the variance of the areas projected on the vertical plane and the horizontal plane to judge the presence of motor interference. The advantage of this approach compared with the former was to avoid the impact of gravity on different waving directions. The drawback of using this method might be that the experimental results were less comparable to many other studies due to the different types of motion and metrics adopted. In the studies presented in this thesis, the more widely adopted approach, i.e. by measuring the movement variances that were orthogonal to the participants' main waving direction (horizontal or vertical) to judge the elicitation of the interference effect, was employed in order to make the experimental results more comparable to the literature.

2.4 Behaviour Adaptation in Human-Humanoid Interactions

In this section, the research background for motor coordination in human-humanoid interaction is presented. Moreover, the method adopted in this thesis for synchrony measurement is discussed.

2.4.1 Motor Coordination

It has been discussed in section 2.2.3 that unconscious motor coordination (mimicry and synchronization) is an important dynamical process in human-human interaction, which can benefit the increase of rapport (Chartrand and Bargh 1999, Wiltermuth and Heath 2009 and Lakin and Chartrand 2003). If motor coordination can facilitate interpersonal interaction, can this dynamical process be adopted to improve human-humanoid interaction? A related effect proposed by Miyashita and Ishiguro (Miyashita and Ishiguro 2004) and Minato et al.'s (Minato et al. 2004) studies was that a humanoid robot with random, natural and unintentional microbehaviours may benefit its acceptability to humans. Although these microbehaviours were not identical to motor coordination, it demonstrated that human-like behaviours might increase the social competence of a humanoid robot and therefore motivate humans to interact with the robot. Marin et al.'s study further suggested that bi-directional motor coordination was a promising direction to enhance robots' social competence (Marin et al. 2009).

Another question has not been discussed here for bi-directional motor coordination between a human and a humanoid robot is whether the human is willing to coordinate his/her movements to the humanoid robot. Past research found that humans might coordinate their movements not only to other humans, but also to other types of stimuli, such as tone (Repp and Penel 2004), a moving light (Buekers et al. 2000) and an oscillating square (Schmidt et al. 2007).

An experiment performed by Dautenhahn (Dautenhahn 1999) investigated temporal coordination between a robot and a human. In that experiment, a participant might shape a mobile robot's behaviour by performing temporally synchronized movements to particular movements of the robot. Dautenhahn's experiment might demonstrate a co-adaptation process between a human and a robot. In this process, the participant might initially adapt his/her behaviour to a pattern that could influence the robot's behaviour. The robot then adapted to the participant's behaviour based on the pattern he/she selected. The results of the experiment indicated that a human might proactively coordinate their movements to a robot.

In the human-humanoid interaction research area, Robins et al.'s study (Robins et al. 2008) found that children adapted the timing of their behaviours to the changes in the timing of a humanoid robot's behaviour in both a drumming interaction game and an imitation interaction game. Their experimental results potentially suggested that humans might also coordinate their behaviours to a humanoid robot's behaviour.

Inspired by the above research, a preliminary attempt to investigate bi-directional motor coordination in human-humanoid interaction is carried out in the present study. The investigation consists of two steps. The first step is to validate whether humans may coordinate their movements to a humanoid robot. The second step is to simulate the motor coordination behaviour mechanism on a humanoid robot. This attempt is proposed to investigate whether a humanoid robot that is capable of coordinating its movements to a human's movement can improve the human's perception to this robot.

2.4.2 Synchrony Measure

In order to realize the motor coordination behaviour on a humanoid robot, it is important to allow the robot to recognize whether a human's actions and its own actions are synchronized. Therefore, a method for measuring behaviour synchrony is required in the present study to indicate the synchronization status between the robot's behaviour and the human's behaviour.

Inspired from Klyubin et al.'s work (Klyubin et al. 2004), which proposed a technique using computational principles that have been shown to model the perception-action loop of an agent acting in its environment in the language of information, the existing method adopted for synchrony measure also employs an information theoretic approach. This method is called the *information distance* method, which was originally proposed by Crutchfield (Crutchfield 1990) based on Shannon's information theory (Shannon 1948). This method calculates the behaviour synchrony between a human and a robot from the spatial and temporal relationships between their movement trajectories. Please refer to section 3.1 for a detailed introduction to this method.

Apart from the information distance method, clearly there exist other methods to identify synchrony. The advantage of using the information distance approach is that it can capture general relationships between sensors instead of only linear relationships (Mirza 2008).

In Olsson et al.'s work (Olsson et al. 2006b, Olsson 2006), five different distance measures (one dimensional Euclidean distance, correlation coefficient, Kullback-Leibler divergence, Hellinger distance, and Jensen-Shannon divergence), together with the information distance, were used as the distance measures in a sensory reconstruction task. The performance of these measures was then compared. The results indicated that the information distance outperformed the other distance measures in this task. The reason behind this might be that the information distance measure took both the individual entropy and the joint entropies of the sensors into account, so that, all functional relationships between sensors were quantified. Mirza's work (Mirza 2008) also supported these findings. In Mirza's study, the information distance measure was compared with three other different measures (simple average, Hamming distance and Pair wise average of Pearson's Squared Correlation Distance). The results suggested that the information distance was more useful in capturing sensorimotor relationships than other measures.

It is arguable whether the information distance measure is the best distance measure method in other applications as the performance of different distance measure methods is very likely task dependent. Nevertheless, the studies mentioned above have already demonstrated the potential usefulness of the information distance method, which enable this method to be applied in a broad area. In this thesis, further research in this domain involves sensors from different modalities, and the relationship between which may be non-linear. Therefore, using a synchrony detection method that is suitable for capturing various types of relationships may benefit the consistency of the present research.

2.5 Research Questions

In this section, the research questions raised in chapter one are revised based on the literature review. The main aim of this thesis is to investigate a valid approach to increase the social competence of a humanoid robot and consequently facilitate its interaction with humans. Inspired from the background research presented above, the dynamical process of motor coordination, which has been demonstrated to be able to facilitate human social interactions (Chartrand and Bargh 1999, Wiltermuth and Heath 2009 and Lakin and Chartrand 2003), may be utilized to improve human-humanoid interaction. Many studies provided support for the feasibility of this approach (Buekers et al. 2000, Dautenhahn 1999, Marin et al. 2009, Minato et al. 2004, Miyashita and Ishiguro 2004, Repp and Penel 2004, Robins et al. 2008 and Schmidt et al. 2007). The three core research questions related to realizing bi-directional motor coordination in human-humanoid interaction are question 2 B), question 3 B) and question 4 B) as listed below (please note that the sequence number of the research questions corresponds to the sequence number used in Chapter 1):

2. B) Can a human's motor coordination be elicited using the same social robot and the same experimental setup as in 2. A)?

3. B) Can a social robot elicit a human's motor coordination compared with a virtual moving dot or a mechanical pendulum?

4. B) Will a human prefer a social robot that adapts to his/ her behaviour compared to a social robot that does not adapt to his/her behaviour?

For research question 2 B) and 3B), the impact of different types of stimuli on humans' rhythmic movements is investigated. Apart from the humanoid robot, the usage of other stimuli is to model the effect of the similar stimuli employed in the previously reviewed studies, such as music (similar to the use of tone in Repp and Penel 2004), a virtual moving dot (similar to the use of an oscillating square in Schmidt et al. 2007) and a mechanical pendulum (similar to the use of hand-held pendulum in Richardson et al. 2005).

In order to answer the above core research questions properly, a few issues need to be addressed prior to these questions as stepping stones. According to the background research, interpersonal synchrony is an important type of coordination behaviour (Bernieri and Rosenthal 1991). In order to realize similar behaviour as interpersonal synchrony in human-humanoid interaction, a real-time synchrony detection mechanism is essential. Hence, the following research questions related to the development and application of a real-time synchrony detection method are raised:

1. Can a method be developed that can be used in real time to detect synchrony in Human-Humanoid Interaction?

4. A) Can the synchrony detection method be developed and used in real-time to help a social robot to adapt its behaviour to a human's behaviour?

The secondary aim of this thesis is to investigate the critical factor related to the elicitation of motor interference in human-humanoid interaction. This aim is motivated by past research that used humans' subconscious reactions to the observed stimuli, the interference effect, as a metric to evaluate the social competence of the observed stimuli (Bouquet et al. 2007, Chaminade et al. 2005, Kilner et al. 2003, Kilner et al. 2007, Kupferberg et al. 2009, Kupferberg et al. 2011, Oztop et al. 2005, Stanley et al. 2007, Sciutti et al. 2012). One of the most controversial issues among these studies was whether the adoption of biological motion was sufficient to elicit the interference effect. Experimental results that supported or opposed this hypothesis were both found when a virtual moving dot or a moving ball was used as the visual stimulus. However, when a humanoid robot was used as the visual stimulus, only the results that supported this hypothesis were found. Therefore, the following research question is brought forward to investigate this issue in human-humanoid interaction.

2. A) Can an interference effect be found in a playful Human-Robot Interaction experiment using a social robot that does not behave according to a biological motion profile?

Another intriguing issue related to the investigation of motor interference was proposed by Stanley et al.'s work (Stanley et al. 2007) about the impact of a human's belief. The perspective that the top-down effect of a human's belief might play an important role in eliciting the interference effect was very different from many other studies that investigated motor interference from a bottom-up perspective. Nevertheless, this top-down effect has not been validated in human-humanoid interaction. Hence, the other question regarding motor interference research is proposed as follows:

3. A) Can a human's belief have an impact on producing an interference effect when interacting with the same robot mentioned in question 2?

2.6 Conclusion

In this chapter, the research background of this thesis is presented. General issues related to the human-robot interaction research area and the development of human-humanoid interaction are briefly introduced to provide a comprehensive background. Afterwards, studies related the motor resonance framework and related behaviours, motor interference, motor coordination and immediate imitation, are critically reviewed and discussed.

Finally, the research questions proposed in Chapter 1 are revised according the background research.

Chapter 3
The Information Distance Method

In this chapter, a synchrony detection method using information distance is introduced. The experimental results illustrated that this method can successfully detect the synchronicity of behaviours between a human and a humanoid robot. A brief introduction and the mathematical background of information distance are given in section 3.1. Section 3.2 depicts the construction of the information distance method. The validation process of this method is described in section 3.3 and 3.4. The conclusion of this chapter is given in section 3.5.

3.1 Introduction to Information Distance

More than half a century ago, Shannon (Shannon 1948) developed *information theory*, which was initially applied in the area of telegraphic communication. Crutchfield (Crutchfield 1990) further discussed an informational theoretic quantity, the *information distance* metric, which is a measure of distance between information sources. Recently, information distance has been adopted in the robotics area due to its capability of capturing informational geometry structure. Applications such as Robot-Environment interaction behaviour characterisation (Mirza et al. 2005a and Kaplan and Hafner 2005), sensorimotor experience similarity measurement (Mirza et al. 2005b), and sensorimotor control development (Olsson et al.

2006a) are developed. In the present study, information distance is employed to capture the spatial and temporal relationships between events, i.e. trajectories of a human arm and a humanoid robot arm, to yield an indication of their behavioural synchrony. In this section, the basic mathematical background of information distance is introduced, followed by the details of how to construct the entire method that was subsequently employed in the studies described in this thesis.

3.1.1 Mathematical Background

In Shannon's information theory, *entropy* is defined as "a measurement of uncertainty of a random variable" (Cover and Thomas 1991). For a discrete random variable *X* with alphabet *Ax*, the probability mass function can be denoted as *p(x)*, where *p(x)* = Pr{*X* = *x*}, value *x* belongs to alphabet *Ax*. The entropy *H(X)* of this variable *X* is defined as:

$$H(X) = -\sum_{x \in Ax} p(x) \log_2 p(x) \tag{3.1}$$

The entropy is measured in bits for log base 2 in the above function. Note that there is an important convention that 0 log 0 = 0, which can be understood as zero probability and does not change the entropy (Cover and Thomas 1991).

For a pair of discrete random variables *X* and *Y* with alphabet *Ax* and *Ay*, the *joint entropy H(X, Y)* of these two random variables is defined as:

$$H(X,Y) = -\sum_{x \in Ax} \sum_{y \in Ay} p(x.y) \log_2 p(x,y) \tag{3.2}$$

The joint entropy is additive if the discrete random variables *X* and *Y* are independent of each other:

$$H(X,Y) = H(X) + H(Y) \tag{3.3}$$

If they are dependent variables, the joint entropy can be achieved by:

$$H(X,Y) = H(X) + H(Y \mid X) = H(Y) + H(X \mid Y) \tag{3.4}$$

H(Y|X) and *H(X|Y)* are the *conditional entropies*, which can be defined as:

$$H(Y \mid X) = \sum_{x \in Ax} p(x) H(Y \mid X = x) \tag{3.5}$$

$$= -\sum_{x \in Ax} p(x) \sum_{y \in Ay} p(y \mid x) \log_2 p(y \mid x) \tag{3.6}$$

$$= -\sum_{x \in Ax} \sum_{y \in Ay} p(x, y) \log_2 p(y \mid x) \tag{3.7}$$

For the two random variables *X* and *Y*, the relationship between their individual entropies, joint entropy and conditional entropies are all illustrated in Figure 3.1. In this figure, the area where *H(X)* and *H(Y)* overlap is called *mutual information*, which measures the amount of information that *X* contains about *Y* and vice versa. The mutual information of two random variables *X* and *Y* is defined as:

$$I(X;Y) = H(X) - H(X \mid Y) = H(Y) - H(Y \mid X) \tag{3.8}$$

$$= -\sum_{x \in Ax} \sum_{y \in Ay} p(x, y) \log_2 \frac{p(x, y)}{p(x) p(y)} \tag{3.9}$$

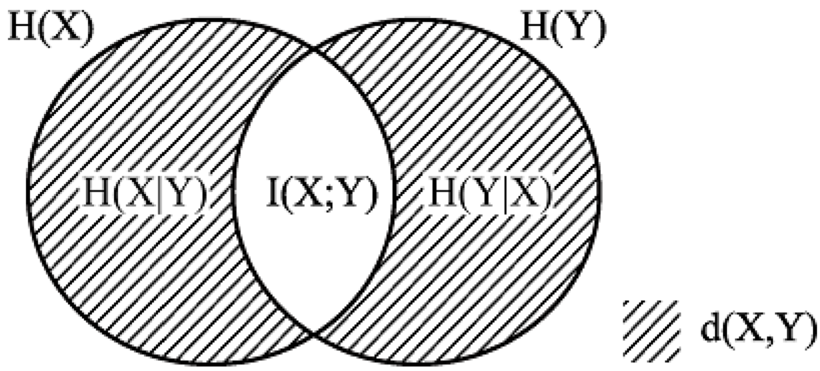


Figure 3.1: This diagram is from (Mirza 2006), which illustrates the relationship between individual entropies, joint entropy, conditional entropies, mutual information and information distance of two random variables *X* and *Y*.

The *information distance d(X, Y)* of the two random variables *X* and *Y*, which measures what variable *X* and variable *Y* do not have in common, is defined as:

$$d(X,Y) = H(X \mid Y) + H(Y \mid X) \tag{3.10}$$

Alternatively, by replacing the conditional entropy elements in function 3.10 with combinations of joint entropy and individual entropy elements presented in function 3.4, the information distance values can be calculated using the following functions:

$$d(X,Y) = (H(X,Y) - H(Y)) + (H(X,Y) - H(X)) \tag{3.11}$$

$$= 2 \times H(X,Y) - (H(Y) + H(X)) \tag{3.12}$$

In the present thesis, a set of discrete random variables are used to model sensors on the arms of a humanoid robot and a human, which record the 3-D spatial positions of the two arms.

One point worth mentioning was that the main advantage of using information distance rather than mutual information was that the information distance had been more widely accepted as a metric mathematically, e.g. it could provide geometry, while the other could not. Information distance, as a metric, has been applied in many studies, such as Olsson et al.'s work (Olsson et al. 2006b), Mirza et al.'s work (Mirza et al. 2005b), etc., and the present work is following the same approach.

3.2 Construction of the Information Distance Method

The synchrony detection method introduced here calculates the information distance between human and robot body part trajectories to yield an indication of their synchrony. Synchronized behaviours are indicated by relatively low information distance values and unsynchronized behaviours result in relatively high information distance values.

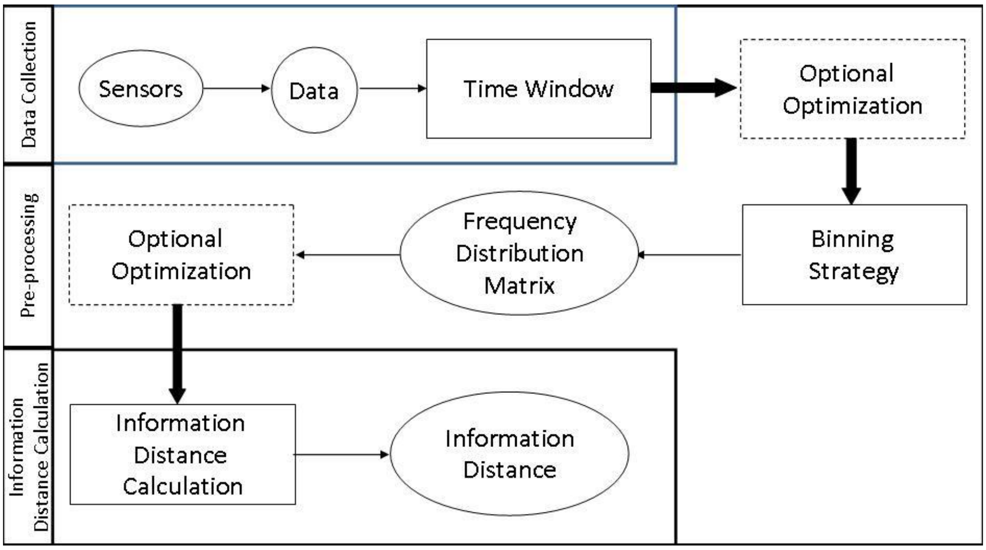


Figure 3.2: this figure illustrates the general construction of the synchrony identification method.

The general construction of the synchrony detection method is illustrated in Figure 3.2. In this figure, circles and ellipses represent data components; rectangles with solid lines represent core processing components and rectangles with dotted lines represent optional processing components.

There are three stages involved in the construction of this synchrony identification method: data collection, which consists of the first three components in Figure 3.2; pre-processing, which consists of the middle four components; and the information distance calculation, which consists of the last two components. These stages will be described in details below.

3.2.1 Data Collection

In the data collection stage, a moving time window is used to store arm movement trajectory data of both a human and a robot. The human arm movement trajectory data can be captured using various approaches, such as a marker detection toolkit, a magnetic motion tracker and a Wii Remote with appropriate software support (for details, please refer to section 3.4.2, 4.2.2 and 5.2 respectively). The robot arm trajectory data is captured by internal sensors of the robot that model actuator positions of the robot arm joint servos. For every time step, the moving time window is updated with the latest collected trajectory data.

The moving time window can be imagined as a two dimensional array. One dimension is the number of time steps of the trajectories that this window can hold (treated as a *row*). The other dimension is the number of variables (i.e. sensors) that are being tracked (treated as a *column*). For example, if the data currently being tracked is the 3-D spatial positions of two arms, one from a human and the other from a robot (x, y, z co-ordinates of both the human and the robot arm spatial positions) and the trajectories being held are the most recent 50 time steps, the moving time window will then hold 50*6 data elements. The size of the time window is fixed within the process of a task and uses the First-In-First-Out queue behaviour. That is, for each time step, the data elements at the back end of the window will be removed and the newly captured data elements will be added to the front end of the time window.

Generally, the estimation of the synchrony should be more accurate with more samples included in the time window. On the other hand, more sample data in the time window usually means longer processing time. As the information distance method is designed to be applied in real-time, the size of the time window has to be carefully considered to ensure the response time for the entire system is reasonable. In this thesis, the size of the sliding time window is therefore task dependent.

3.2.2 Binning Strategy

The binning strategy component of the information distance method is used to extract data distribution features. These features are recorded using a frequency distribution matrix and two bin frequency distribution arrays, which will be described below. They are the critical source of information for conducting the information distance calculation in the next stage.

In order to estimate the probability mass function $p(x)$ (in function 3.1) for a discrete random variable X, a commonly used approach is to adopt a binning strategy, with which the alphabet A_x of variable X can be divided into several bins and $p(x)$ can be estimated from the frequency distribution of the bins. In this study, the data held in the time window is allocated into different bins according to its value and the binning strategy employed. During this process, the frequency distribution matrix tracks how many times data items in bin a of variable X have appeared together with data items in bin *b* of variable *Y*. The frequency distribution arrays track the number of times data items in each bin of their own variable have appeared.

A novel binning strategy used in this similarity identification method is named as *Partial-Adaptive Binning Strategy*. It is developed from the uniform binning strategy described in Olsson et al.'s work (Olsson et al. 2005). However, these two binning strategies have significant differences due to the differences between the nature of the data in these two studies. In Olsson et al.'s work, the data represented pixel values of a robot's vision system, which had similar inputs and all inputs were from sensors of the same agent. However, in the present study, the input data represent agent body part movement trajectories and the inputs are from sensors of different agents (a human and a humanoid robot). Therefore, there may be large variances in the data captured. Using the original binning strategy may cause a loss of a significant amount of information.

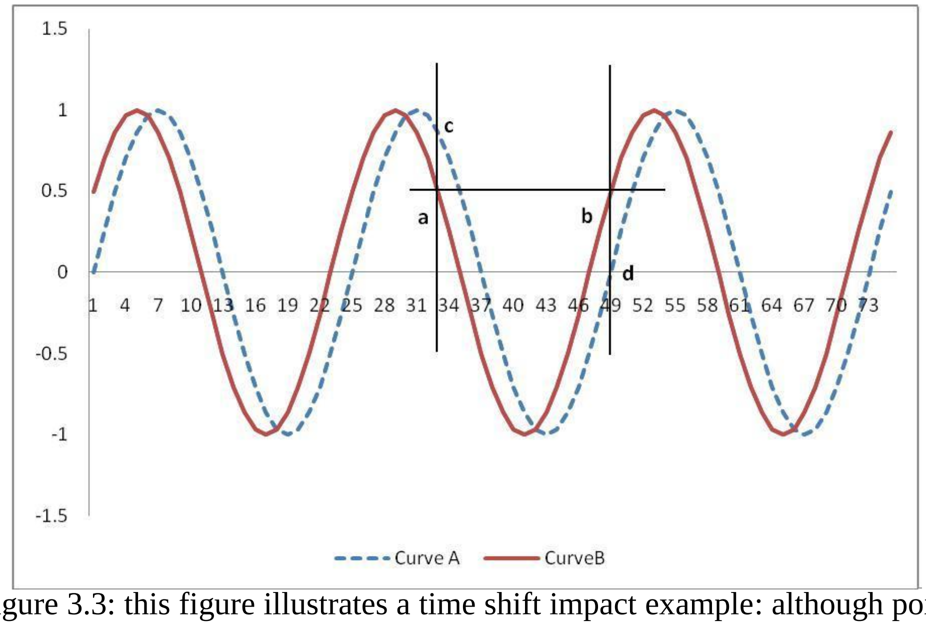


Figure 3.3: this figure illustrates a time shift impact example: although point *a* and point *b* on curve *B* have the same value, the difference between their corresponding points (*c* and *d*) on curve *A* is significant.

The partial-adaptive binning strategy has two new features: ‘independent bin range adaptation’, and ‘tendency separation’. ‘Independent bin range adaptation’ means that the bin range (which refers to the value range between the upper boundary of the upper most bin and the lower boundary of the lower most bin) of each variable depends only on the input data of this variable within the time window and is independent of the input data of other variables. The bin range is determined by the maximum and minimum input data of this variable. This feature caters for the fact that different variables model data from different sensors and the range of their data values may have significant differences. Therefore, the data features of different variables may be omitted if the same bin range is applied across the entire time window instead of within each individual variable.

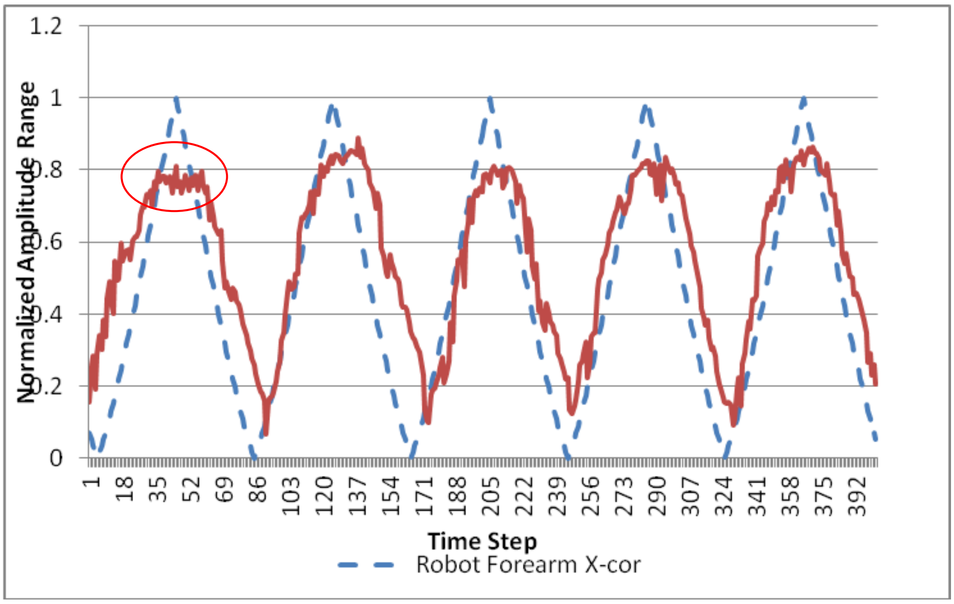


Figure 3.4: this figure illustrates the forearm X-axis trajectories of a robot and a human in human-humanoid imitation interaction, in which the human is trying to imitate the humanoid robot’s waving behaviour. The “zig-zag” parts are illustrated and highlighted using an ellipse.

‘Tendency separation’ means the tendency of a data item (i.e. whether the next data item of the same variable has a larger or smaller value than the current one) is considered in the bin allocation process. Practically, each bin is split into two bins: an ascending bin and a descending bin. Once a data item is allocated into a bin, the tendency of this data item is examined. If the tendency is rising or staying still, this data item is assigned to the ascending bin. Otherwise, it will be assigned to the descending bin. Tendency separation is used to reduce the impact of the delay (or time-shift) in imitation or coordinated behaviours. For example, there might be a slight delay between a human trying to copy the actions of a robot, or vice-versa.

An example of time shift impact is presented in Figure 3.3. Curve *A* and curve *B* are identical except curve *B*'s position is slightly shifted. Although point *a* and point *b* on curve *B* have the same value, the difference between their corresponding points (*c* and *d*) on curve *A* is significant. If the data value is the only concern, point *a* and point *b* will be allocated to the same bin, say bin *x*, while *c* and *d* are very likely to be allocated to different bins, say bin *y* and *z*. Consequently, this one-to-many ($x \rightarrow y$ *and* z) relationship causes an ambiguity and omits the fact that there is one-to-one relationship existing if the tendency factor is considered. Figure 3.4 shows forearm X-axis trajectories for both a robot and a human (where a human was attempting to replicate a robot movement). This figure illustrates the existence of this time shift impact in real life: the human's movements may be faster or slower than the robot's movements. In real-world human-humanoid imitation interactions, 'perfect' synchronization behaviour is unlikely as there is usually some difference in the timing between the behaviours of the two agents.

Another binning strategy developed from Olsson et al.'s work is named as Complete-Adaptive Binning Strategy. This binning strategy, inspired from the idea of entropy maximization (Olsson et al. 2005), allows the bin size (which refers to the range between the upper boundary and the lower boundary of a bin) to vary in order to ensure each bin contains the same number of data items so that the entropy value can reach the theoretical maximum. By contrast the partial-adaptive binning strategy has a fixed bin size which only varies as the consequence of the variance of the bin range and all bins have the same size.

As the information distance method with partial-adaptive binning strategy is already capable of providing synchrony indications between the behaviours of two agents, the complete-adaptive binning strategy is not applied in the later experiments. The main reason is simplicity as the time scale and the number of participants required may have to be doubled if both binning strategies need to be fully tested and validated in all experiments. In addition, the application of tendency separation and entropy maximization may conflict with each other in some special cases. For example, if the tendency of incoming sensor data is always rising within a period of time *T*, all the data items will be allocated into rising bins and descending bins won't get any data item. However, according to entropy maximization, each bin should have equivalent number of data items regardless of descending bins or rising bins. Without the tendency separation feature, the complete-adaptive binning strategy may not handle the time-shift impact properly and consequently affect the performance of the whole method in synchrony detection. How to resolve this conflict issue in the application of the complete-adaptive binning strategy is marked as a subject for future research.

The application of different binning strategies may entirely change the output results from the information distance calculation. As a binning strategy is applied prior to the information distance calculation, changes made to the binning strategy will cause changes to the data distribution features extracted. Hence, the choice of the binning strategy will have a critical impact on the final output of the entire method.

3.2.3 Pre- and Post-binning optimization

There are two optional optimization components at this stage. The one prior to the binning strategy component is called *pre-binning-optimization* and the other is called *post-binning-optimization*.

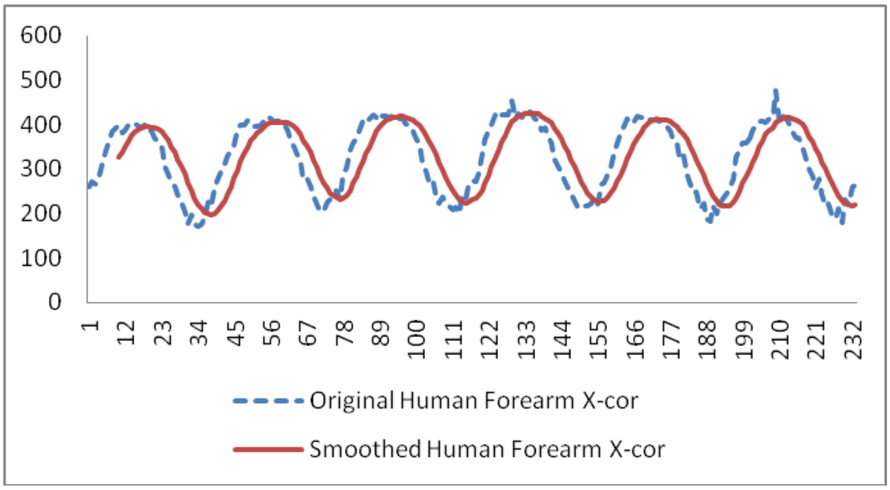


Figure 3.5: this figure illustrates the effect of the curve smoothing method, which filters the “zig-zag” parts of the agent behaviour trajectory curves.

The purpose of pre-binning-optimization is to reduce the impact of noise occurring during the data collection stage (such as sensor misdetection). The present pre-binning-optimization method employed is curve smoothing, which filters the “zig-zag” parts of the agent behaviour trajectory curves (Figure 3.4 illustrates a human forearm X-axis trajectory curve and the “zig-zag” parts on the curve are highlighted using an ellipse), which may confuse the binning strategy component in detecting the forearm movement tendency. These “zig-zag” parts may arise from two factors: either the human imitation behaviour is not performed smoothly, or the sensors are affected by environmental noise. The current strategy applied to curve smoothing is to take the average of the values of the original data point and its preceding neighbours as the new value of the data point. This procedure resulted in a temporal shift in the curves. The effect of this curve smoothing method is presented in Figure. 3.5.

In this study, the post-binning-optimization method introduced is called ‘*winner takes neighbours*’. The purpose of this post-binning-optimization is similar to the ‘tendency separation’ feature introduced before: to reduce ambiguity and enhance possible correlation between bins from two variables being compared and therefore reduce the impact of time shift.

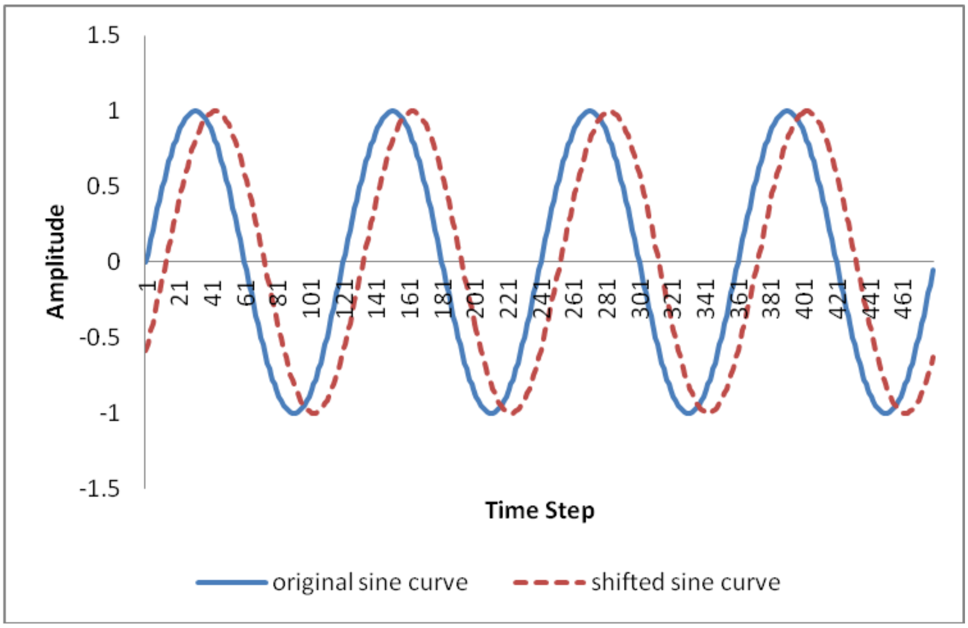


Figure 3.6: this figure illustrates a sample sine curves and one of its shifted versions used in sine curve data validation

In an ideal model, the incoming data of a sensor is evenly distributed spatially and temporally according to a particular pattern (for example, the sine curve illustrated in figure 3.6). If that is the case, the correlation between bins can be captured relatively easily even there is an impact of time shift. However, in the real world, the data collected may not be evenly distributed due to environmental noise and detection errors. Under these circumstances, the impact of time shift may magnify the distribution problem and consequently increase the difficulty of detecting possible correlations between bins. For this reason, the 'winner takes neighbours' optimization method is introduced to help enhance the possible correlation between bins.

The principle behind this method can be explained using the following example: if bin *y* of variable *A* appears with bin *m* of variable *B* more often than any other bin of variable *A*, say 9 times. Then the number of times that bin *y*'s neighbours (bin *x* and bin *z*) appear with bin *m* of variable *B*, say 2 times and 3 times respectively, will be added to the previous 9 times of bin *y*. Then it becomes 14 times for bin *y* all together. The frequency distribution matrix and the two frequency distribution arrays are updated accordingly. Thus, the one-to-one relationship between bin *y* and bin *m* is enhanced. The stronger the one-to-one relationship between two bins is, the more likely they are correlated. This optimization method is applied with the assumption that the data ought to be assigned to bin *y* is accidently assigned to bin *z* or bin *x* due to the uneven data distribution and time shift impact. Please note that this optimization method is an empirically based method and its application is task dependent.

3.2.4 Information Distance Calculation

The information distance is calculated between two variables, usually a pair of corresponding behaviour components from behaviours of a human and a robot respectively (for example, the x co-ordinates of the human forearm trajectories and the x co-ordinates of the robot forearm trajectories). The information distance between two variables *X* and *Y* is defined as the sum of the conditional entropies of these two variables, which can be calculated using formula 3.12 in section 3.1. The entropies presented in that formula can all be derived from the data distribution features extracted using the binning strategies. The joint entropy of variable *X* and *Y* can be calculated using the frequency distribution matrix. The individual entropies of variable *X* and *Y* can be calculated from the frequency distribution arrays.

3.3 Artificial Data Validation

In order to validate whether this similarity identification method can successfully identify synchrony, a validation process was conducted. Please note that the winner takes neighbours optimization strategy was not applied in the first two validation steps because there was no time shift impact involved in the test models of these two steps.

3.3.1 Random Data Validation

The first step of the validation process was to use randomly generated data to check whether the information distance method could identify identical data patterns, which could also be regarded as perfectly synchronized behaviour patterns. The results showed that the identical data patterns were successfully identified as the resulting information distance value between them was zero (0).

3.3.2 Waving Behaviour Model Validation

The second step of the validation process was to use 3-D movement trajectories generated by Matlab (The MathWorks Inc. 2008) which modelled interaction between a human and a robot using waving behaviours. Compared with the behaviour trajectory data recorded from experiments using an embodied robot, the modelled trajectory data was much simpler (the data model was a simple arc). This validation step was to model an ideal scenario where the waving behaviours of a human and a robot were completely synchronized. This scenario could also be understood as a human imitating a robot's behaviour and the imitation behaviour was perfectly timed. There was very little difference between the 3-D trajectories of the human and robot forearm. The only difference was that the robot model and human model had different arm length settings. The results indicated that the information distance method could identify these completely synchronized behaviours (and could also be understood as completely synchronous imitation behaviours) as the resulting information distance value between them was zero (0).

3.3.3 Sine Curve Data Validation

The third step in the validation was to use sine curve data to check whether the information distance method could handle time step shifts. That is, the information distance method was applied to calculate the information distance between a sine curve and the same sine curves with shifted time steps. The time steps shifted were used to simulate behavioural delay in real life. If this method could successfully identify identical sine curves with a small number of time steps shifted, it was very likely that it could also be used to identify synchronous or coordinated behaviours with reasonable delay. A sine curve was chosen because it is an ideal continuous periodic data model and the repeated waving behaviour introduced in section 3.4.1 was also continuous and periodic. In this validation step, the number of time steps shifted continuously increased until one complete period cycle was shifted. The performance of the information distance method was recorded during the shifting process. An example of shifted sine curve is illustrated in Figure. 3.6.

The sine curve data validation result of the information distance method is illustrated in Figure 3.7. In this figure, the curve depicted with a solid line was the information distance results calculated with the ‘winner takes neighbours’ optimization strategy; the curve depicted with a dotted line was the information distance results calculated without the ‘winner takes neighbours’ optimization strategy. For both curves, there were three common points in the entire shifting process where the information distance between the original sine curves and the shifted sine curve fell to a low value. As one complete period cycle of the sine curve had 120 time steps, at the 1st time step and 121st time step, the two sine curves were actually on top of each other. That was why the information distance between them was 0. At the 61st time step, when the two sine curves were completely opposite (i.e. at a particular time *t*, while one curve reached its local maximum, the other curve reached its local minimum), the information distance between them also went down. As both mappings (completely same and completely opposite) indicated the existence of strong information correlation, the validation of the information distance method could be considered as successful. Thus the method served to indicate both when the human was (mirror) matching the actions of the robot, and also when the human was matching but was perfectly opposite, both of which might be considered to be similar and synchronous behaviours. The ‘noise’ in Figure 3.7 actually represented that there were quite a few local minima on the information distance value curves. These local minima often emerged when relatively stronger one-to-one correlation among the bins appeared, although the correlation was not as strong as when the two sine curves were completely opposite or on top of each other. According to the algorithm of the information distance method, each time the data items in the time window were updated, the distribution of these data items in each bin had to be re-calculated and result might be quite different from what the distribution was in the previous time step. This might explain why the information distance curves were not smooth

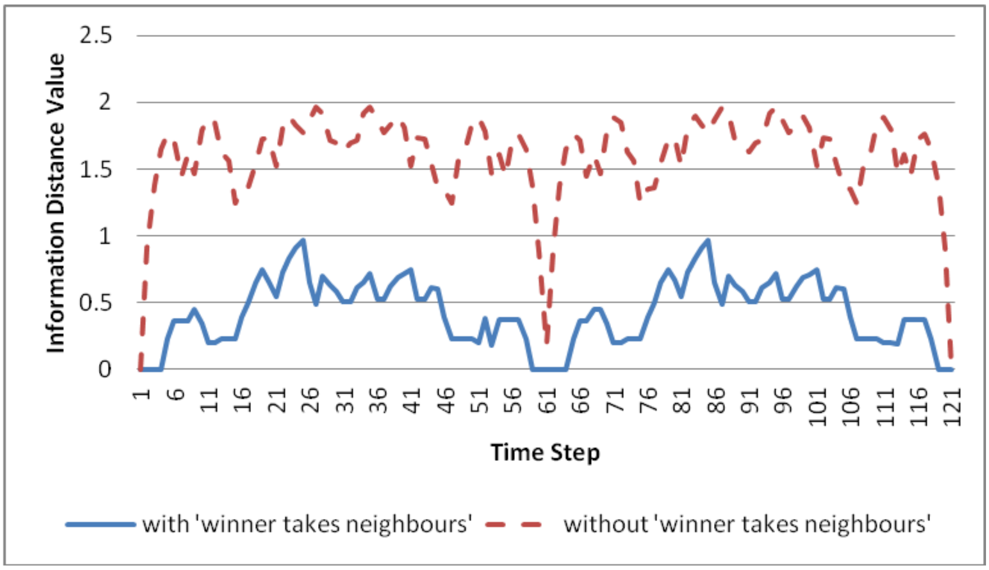


Figure 3.7: this figure illustrates the sine curve data validation results: the curve depicted with solid line was the information distance results calculated with the ‘winner takes neighbours’ optimization strategy; the curve depicted with dotted line was the information distance results calculated without the ‘winner takes neighbours’ optimization strategy

Furthermore, the validation results also demonstrated the importance of the ‘winner takes neighbours’ optimization strategy. In Figure 3.7, once there was a small number of time step shifts, the dotted line curve rose immediately. By contrast the solid line curve remained at level 0 for a few time steps and then started to rise. In addition, the overall information distance level of the solid line curve was much lower than the information distance level of the dotted line curve. These phenomena indicated that the information distance method was much less sensitive to the time shifts with the help of the ‘winner takes neighbours’ optimization strategy. Moreover, if the number of time steps shifted was within a small range (in this case, less than or equal to three time steps), the original sine curve and the shifted sine curve were still identified as identical. This result suggested that the information distance method with the ‘winner takes neighbours’ optimization strategy might successfully handle reasonable time delay in real-life. In all the subsequent experiments included in this thesis, the 'winner takes neighbours' optimization strategy was constantly applied together with the information distance method.

3.4 Embodied Robot Trajectory Validation

The above validation steps demonstrated that the theoretical performance of the information distance method had met its design purpose, i.e. it could successfully identify completely identical data pattern models, completely opposite data pattern models and completely identical data pattern models with simulated delay (time shift). However, variances in real life were usually much more complicated than theoretic models. Therefore, the performance of this synchrony detection method should be further validated with real life human-humanoid interaction data.

3.4.1 Experimental Design

The data used for this experiment was collected from three imitation games. In the first game, a human experimenter imitated the forearm waving behaviour of a humanoid robot (regarded as *same direction imitation*). In the second game, a human experimenter imitated the forearm waving behaviour of a humanoid robot, however, in an opposite direction (regarded as *opposite direction imitation*). In the third game, a human experimenter did not do anything when a humanoid robot was waving its arm and started to wave his arm when the humanoid robot was doing nothing (regarded as *unsynchronized behaviour*).

It was hypothesized that the level of information distance values in the first game and the second game was relatively low as both same direction imitation and opposite direction imitation were regarded as synchronous behaviours. The level of information distance values in the third game was expected to be relatively high due to the unsynchronized behaviour between the robot and the human in this game.

Figure 3.8: KASPAR interacting with a child, the KASPAR figures are sourced from (University of Hertfordshire 2007)

As a starting point in the investigation of the method presented, the behaviours to be imitated were not expected to be complex. Therefore, the behaviours chosen involved only forearm waving while the upper arm was kept stationary. This reduced the complexity of the imitation.

The humanoid robot used in the above games is called KASPAR, and was developed by the Adaptive Systems Research Group at the University of Hertfordshire. KASPAR is a child-sized humanoid robot with 14 degrees of freedom (8 in head and 6 in arms) (Blow et al. 2006). The robot has been designed specifically for the purpose of engaging people in socially interactive behaviour. The robot is, for example, able to perform certain face, head and arm gestures that have been used in human-humanoid interactions e.g. with a child illustrated in Figure 3.8 and Robins et al.'s work (Robins et al. 2008).

3.4.2 Immediate Imitation

In order to realize the forearm waving imitation interaction in this experiment and possible future bidirectional human-humanoid imitation interactions between a human and a humanoid robot, an immediate imitation mechanism was required for the humanoid robot. Through this mechanism, the body part movements of a subject could be tracked and immediately responded to with similar movements. To achieve this aim, some fundamental issues needed to be solved. First of all, the robot should be capable of detecting the object to be imitated so that the actions and states of the object could be tracked.

Object Detection

In this experiment, the embedded vision facility of the humanoid robot using two black and white cameras at the eye positions of the robot were used as the perception system to detect human body parts.

Two commonly used approaches to object detection by robot vision systems had been investigated. One approach was to utilize particular features of the objects themselves in the detection, such as in face detection. The other one was to add particular features (markers) to the objects to make them detectable. Several object detection techniques were explored in this thesis and their advantages as well as drawbacks are listed below:

Face Detection was implemented using the OpenCV library (Agam 2006). This library provided a pre-trained mechanism which encoded the general profile features (involving the position of two eyes and mouth) of human faces.

Advantages:

1. The detection was fully automated, no need to pre-specify target.

2. Human face was more natural than many artificial objects and it allowed the robot to interact with human being without external aid.

Drawbacks:

1. Could be confused by background noise. For example, if there were three black points in the background which happened to be distributed like eyes and mouth, the program might misclassify these points as a human face.

2. The degree that a human face allowed to turn was restricted within a certain range. As the turning of the face might affect the profile of the face presented and cause misdetection.

3. Could be affected by the light source.

Colour Object Detection was also implemented using the OpenCV library. The detection was realized by computing the colour histogram of a specified object and used this colour histogram to detect the presence of the object. Please note that as the vision system of the robot in these experiments was using black and white cameras, the colour object detection experiment was conducted using an external colour camera placed on the top of the robot's head.

Advantages:

1. Rarely affected by the light source.

2. Rarely affected by the change of object profile.

Drawbacks:

1. Target object needed to be pre-specified at the beginning.

2. The background should not have similar colour as the specified object.

3. Additional colour camera was required.

Gray-Scale Object Detection was implemented to investigate whether using a gray-scale level could achieve a similar detection effect as the colour histogram. The gray-scale object detection used the robot's own vision system. The general idea of the method was similar to the colour object detection, except using gray-scale values to replace colour histograms. The results showed that the detection was seriously affected by the light source. The shade in the background caused by the light source could easily mislead the detection.

Marker Detection was realized by using an open source toolkit, ARToolkit (Kato and Billinghurst 1999). ARToolkit could detect pre-trained markers and return the marker transformation information. From the transformation information, the 3-D position and the orientation of the marker in the camera co-ordinate system could be extracted.

Advantages:

1. The detection was fully automated, no need to pre-specify target.

2. Rarely affected by the noise.

3. Spatial data could be obtained.

Drawbacks:

1. Could be affected by the change of pattern profile, for example, rotation.
2. Could be affected by the light source.

From the above investigation of object detection techniques, the sequence of the object detection reliability of these four object detection methods was: colour object detection > marker detection > face detection > gray-scale object detection. As using the robot's own vision system was preferred in this experiment, the marker detection method was chosen. The additional function of returning object spatial position data was also a big advantage, which made the goal of object position tracking straightforward to achieve.

The Correspondence Problem

The second issue to be solved was that appropriate correspondences between the human and the humanoid robot in imitation dynamics, such as actions, states and goals, need to be addressed. This correspondence issue was known as *the correspondence problem* (Nehaniv and Dautenhahn 2002). As the behaviour to be imitated in this experiment only concerned forearm waving, the correspondence problem was solved explicitly by mapping human elbow joint angles to robot elbow servo readings.

The number of degrees of human elbow joint angle could be extracted from the transformation information returned by ARToolkit. The actual mapping between the human elbow joint angle degree and robot elbow servo readings was resolved by applying an empirical exchange rate. Once the mapping was established, the 3-D trajectories of the robot arm during the experiment could be estimated from the changes of the robot elbow servo readings as both the main body and the upper arm of the robot was kept stationary during this experiment. After the experiment, both the collected human arm movement trajectories and the estimated robot arm movement trajectories were needed to perform the validation of the information distance method. Having addressed the correspondence issue, the forearm of the humanoid robot KASPAR could immediately imitate the forearm movements of a human experimenter with the help of the marker detection toolkit.

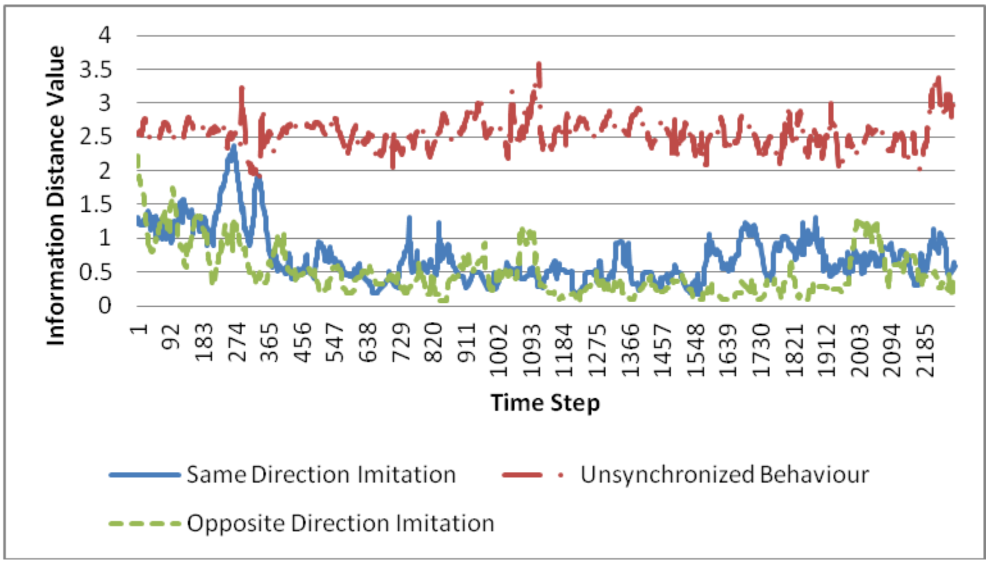


Figure 3.9: this figure illustrates the results of the information distance method validation using real human-humanoid imitation interaction data

Although the robot was not imitating any human behaviour in these games, it required the robot to have equivalent capability of immediate imitation. The ability of detecting and tracking human body part movements and mapping them to the body parts of the robot itself was critical to this experiment.

3.4.3 Results and Analysis

The results of the information distance method validation using real human-humanoid imitation interaction data are illustrated in Figure 3.9. In this figure, the unsynchronized behaviour information distance curve was significantly higher than the same direction imitation information distance curve and the opposite direction imitation information distance curve. In addition, the same direction imitation information distance curve and the opposite direction imitation information distance curve were close to each other. These phenomena were expected as they matched the general outline of information distance calculation: less synchronized events resulted in higher information distance values and vice versa. These results matched the hypothesis presented in section 3.4.1 and implied the information distance synchrony identification method could successfully identify the synchrony of the imitation behaviour between a human and a humanoid robot.

3.5 Conclusion

In this chapter, a synchrony detection method using information distance, which is based on information theory, is introduced. Experiments were carried out to validate the method using simulated data and real-world human-humanoid imitation interaction data. The validation results suggested that the information distance method is capable of identifying synchronous behaviours in the interaction between a human and a humanoid robot. The application of appropriate binning strategies is suggested to be the key factor that drives the effectiveness of this method. In addition, the immediate imitation behaviour is realized on a humanoid robot to mediate the robot's action perception and action production, which establishes a baseline for realizing more complex social behaviours in future research.

Chapter 4
Motor Interference and Motor Coordination Experiments

4.1 Introduction

In this chapter, two experimental investigations concerning movement interference and movement coordination in human-humanoid interaction are reported. The experimental settings of both experiments were initially inspired by Oztop et al.'s work (Oztop et al. 2005). In Oztop et al.'s work, human participants were instructed to interact with a humanoid robot by performing congruent and incongruent arm movements. From the reaction of the participants, i.e. whether the participants' movement variances significantly increased when the participants and the humanoid robot were performing incongruent movements compared with their movement variances when performing congruent movements, it could be implied whether motor interference had emerged in the human-humanoid interaction.

In the two experiments presented in this chapter, a humanoid robot with more human-like appearance (compared with the DB robot used in Oztop et al.'s work) was employed. The experimental setup was designed to be less constrained than in Oztop et al.'s work with an emphasis on playful interaction. The differences between the experimental settings of Oztop et al.'s experiment and the two experiments reported in this thesis are summarized in Table 4.1 in section 4.2.1.

The motor interference investigation in this chapter starts from human-humanoid interaction and then extends to the interaction between a human and other agents, such as a mechanical pendulum and a virtual moving dot. The reaction of human participants when they were interacting with the humanoid robot and other agents was compared and analyzed to evaluate what factors were critical to elicit motor interference. In this chapter, different factors in human-humanoid interaction are introduced in different experiments respectively. For example, the music factor and the participant age group factor are introduced in the first experiment and the participants' belief factor is included in the second experiment.

Apart from motor interference, motor coordination in human-humanoid interactions was also investigated in the two experiments simultaneously. In these two experiments, the behavioural rhythm of the participants was not restricted. Therefore, the participants might choose their own behavioural rhythm during their interaction with different agents. Consequently, the behavioural synchrony between the participants and the agents might reflect the subconscious willingness of the participants to coordinate their behaviours to these visual stimuli, which potentially indicated their preference to different agents. Please note that the word 'rhythm' in this thesis means "a strong, regular repeated pattern of movement or sound" (Oxford Dictionaries 2011). The information distance synchrony detection method introduced in chapter 3 was applied in both experiments to measure behavioural synchrony.

4.2 Experiment I

4.2.1 Introduction

As a starting point, the first experiment reported in this chapter only concerned human-humanoid interaction. In this experiment, the following issues were explored: 1) the existence of an interference effect in a playful human-humanoid interaction experiment using a humanoid robot with human-like appearance but without a biological motion profile, 2) the impact of music on human behaviour in human-humanoid interaction, 3) the differences between children and adults' behaviours in terms of motor interference and motor coordination in human-humanoid interaction and 4) the impact of robot behaviour rhythm on the rhythm of human behaviours in human-humanoid interaction.

The playfulness of the interaction with the robot was introduced due to their appropriateness for child participants. With the emphasis on playful interaction, the arm movement behaviour adopted was designed to be simple and natural. Two basic arm movement behaviours were used in the first experiment: vertical waving and horizontal waving. For both waving behaviours, the upper arm of a subject remained still and the subject used only the forearm to wave vertically or horizontally. Therefore, the hand trajectories of the subject were curvilinear instead of linear, which was more natural and easy for both a human and a humanoid robot to produce. As stated in section 4.1, the speed or rhythm of the participants' waving behaviours was not restricted. In contrast, the arm movement behaviours in Oztop et al.'s experiment were restricted to linear movements and the rhythm of arm movements was restricted to 0.5 HZ.

Table 4.1: this table illustrates the comparison of experimental settings among Oztop et al.'s experiment and the two experiments presented in this chapter.

Experiment Setup Items		**Oztop et al.'s Experiment**	**Experiment I**	**Experiment II**
Waving behaviour	***Direction***	Top-Right to Bottom-Left / Top-Left to Bottom-Right	Vertical / Horizontal	Horizontal
	Frequency	0.5HZ	Not specified	
	Trajectory	Linear	Curvilinear	
	Arm used	Whole arm	Forearm only	
Participants	***Age***	Adults	Adults / Children	Adults
	Distance to the Agent	2m	Around 1 m	
Instructions given		Detailed instructions	General instructions	General instructions with engagement implication
Agent		Robot / Human	Robot	Robot / Pendulum / Virtual moving dot
Agent Behaviour Profile		Biological motion profile	Non-biological motion profile	
Music		No music	Music on / off	No music
Robot Platform		 DB	 KASPAR2	

Apart from the arm movement behaviours, there were quite a few differences among the original experimental settings of Oztop et al.'s work and the experimental settings employed in the present two experiments. A detailed comparison of these differences is illustrated in table 4.1.

The robot platform used in the present two experiments is called KASPAR2. It was developed by the Adaptive Systems Research Group at the University of Hertfordshire. KASPAR2 is a child-sized humanoid robot with 18 DOFs (degrees of freedom). It has 5 DOFs in each arm, which enables it to perform some basic movements. KAPSAR2 is an update version of the humanoid robot KASPAR introduced in chapter 3. It has a body of an elder child than KASPAR’s body. Moreover, it also has more DOFs in arms than KASPAR so that it can perform more complex arm movements. In these two experiments, KASPAR2 only used its right arm to wave either horizontally or vertically (illustrated in Figure 4.1).

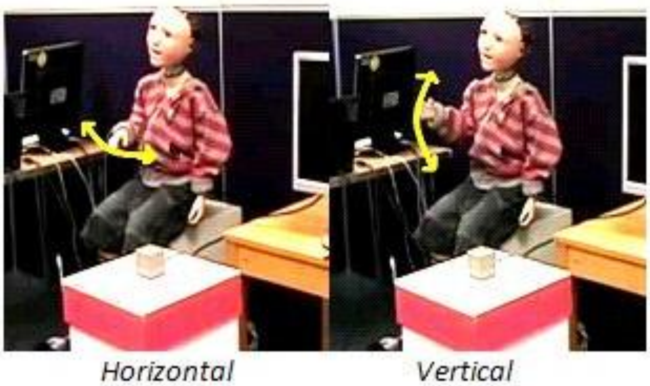


Figure 4.1: Illustration for KASPAR2’s arm movements in horizontal and vertical direction.

According to Press et al.’s work (Press et al. 2005 and Press et al. 2006), the appearance of a robot might have an effect on eliciting the interference effect. As KASPAR2 has a more human-like face and more human-like arms compared with DB used in Oztop et al.’s work (Oztop et al. 2005), it was expected to find a significant interference effect in this human-humanoid interaction experiment. It was also possible that other factors might influence the outcome of the experiment, such as lack of a biological motion profile and the more playful and less constrained setup of the interaction. It was also expected that the application of music, the rhythm of which was generally in phase with the robot's movement rhythm, would facilitate the elicitation of motor interference. In addition, with the music factor introduced, the participants' movements and the robot's movements were expected to be more synchronized when the music was on and less synchronized when the music was off. Moreover, since different levels of engagement of children versus adults interacting with a robot could be expected, the reactions of children and adults in the interactions were expected to be different. Finally, it was expected to find that participants would coordinate their movement rhythm to the robot's movement rhythm since previous research with KASPAR by Robins et al. has shown that children tended to adapt the timing of their movements to the robot's movements (Robins et al. 2008).

4.2.2 Experimental Design

Participants

There were altogether fourteen children and fourteen adults participating in the first experiment. All participants were right-handed. The child participants were from St. Matthew Academy, Blackheath, London and the adult participants were students (undergraduate or postgraduate) or staff from the University of Hertfordshire. In the video investigation after the experiment, it was found that 4 child participants did not follow the experimental instructions correctly, which affected the effectiveness of their experimental data. For example, one child did not look at the robot when he was waving his arm. Therefore, the experimental data of these 4 children were excluded from the data analysis.

Waving Behaviours and Music

Apart from the description of the waving behaviours given in section 4.2.1, please note that KASPAR2's waving behaviours were synchronized with a music track, which was a nursery rhyme: "Baa Baa Black Sheep". A nursery rhyme was selected to test the impact of music in this experiment because it was expected that people might be more familiar with nursery rhymes and therefore found it easier to get involved in the music rhythm. In addition, many nursery rhymes have a relatively slow and constant rhythm, which might facilitate better synchronization between the participants' movements and KASPAR2's movements.

The specified nursery music track was about 30 seconds long and had a constant rhythm. The time interval between each beat in the music was 1.03 seconds and KASPAR2's waving behaviour was set to spend approximately 2.06 seconds to complete one single wave movement. That is, every single wave movement (for example, from left to right) of KASPAR2 took two beats and every complete back and forth wave movement (left to right then left again) took four beats. During the whole experiment, KASPAR2 was set to wave at a constant speed. The transition between the with/without music condition was realized by simply switching on or off the computer speakers. The presence of the with/without music condition were randomized.

Data Collection

A Polhemus Liberty magnetic motion tracking system (www. Polhemus.com 2009) was used in this experiment to track the hand movement trajectories of both the human participants and KASPAR2. Two magnetic sensors were attached on the waving arms of both human participants and the humanoid robot to collect the 3-D spatial position data.

The magnetic motion tracker system returned the Cartesian coordinates of the sensors with respect to a magnetic source block with a frame rate of 240 frames per second.

Participant Instructions

During the experiment, the participants were asked to follow some instructions. In order to make the human-humanoid interaction more playful, human participants were not specially trained to perform certain movements. The instructions given were very general instead of specifying every single detail:

1. Each participant was asked to stand facing KASPAR2 within a given distance (around one metre).
2. Each participant was asked to only use their right arm in the experiment. However, the amplitude, speed and rhythm of their movements during the experiment were not restricted. That is, the participants did not have to follow the moving speed/rhythm of the humanoid robot. Instead, they could control the speed/rhythm themselves.
3. Each participant was asked to concentrate on KASPAR2’s waving arm when waving his or her arm.
4. Before starting an experimental trial, the instruction of waving direction, either horizontally or vertically, was given to each participant depending on whether his or her movements were supposed to be congruent or incongruent with the observed movements in that trial.

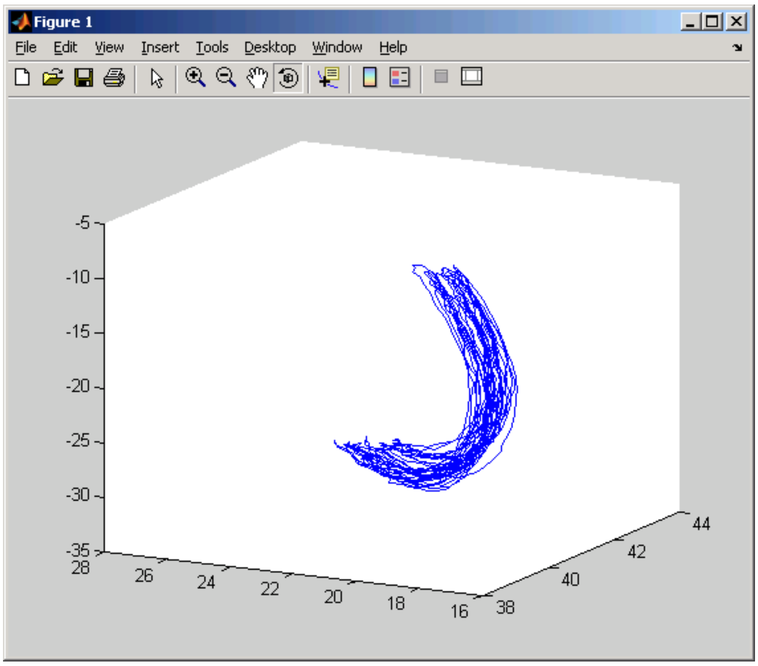
Procedure

Before starting the experiment, each participant was given a demo of the two basic waving behaviours described earlier by an experimenter. Afterwards, each participant was advised to practice the movements a few times to get familiar with the movements. Then, the participant was instructed to interact with KASPAR2 for 8 trials. These trials represent different experimental conditions according to 3 variables: participants' arm movement direction (vertical/horizontal), behaviour congruency in human-humanoid interaction (congruent/ incongruent) and the presence of the music effect (with music/ without music). Each trial lasted around 30 seconds. Participants were informed when to start before each trial and when to stop after each trial.

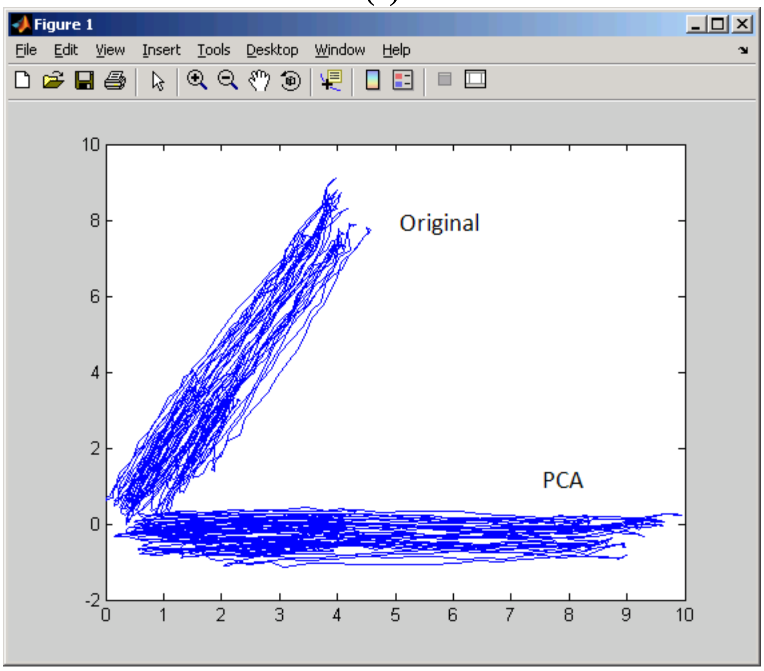
Measurement

In this chapter, the possible interference effects were quantified by the standard deviation of the movement trajectory positions within the plane orthogonal to the dominant movement dimension. For example, when a participant was waving horizontally, the x-y plane was the dominant movement plane. Therefore, only the coordinates in the z-dimension were used to measure the interference effect.

When a subject was waving vertically, it was more complex to locate the movement variances. This was because, in the experiment setup, the magnetic source block was placed diagonally to the participants in order to ensure the accuracy of the measurement. Due to the environmental magnetic interference and the restrictions in the magnetic field generated by the Polhemus device, the usable range and position of the magnetic field had to be limited to maintain the accuracy of measurement. Consequently, there was no axis (x, y or z) orthogonal to the subject's main motion plane in the vertical waving condition.



(a)



(b)

Figure 4.2: (*a*) Illustrates an example of human participant hand trajectories in 3-D space for the vertical waving condition; (*b*) illustrates the mapping of the trajectories in figure *a* on the horizontal plane and the results after PCA. The main motion direction of the mapped trajectories after PCA was orthogonal to one of the axes.

An alternate approach applied was to take the mapping of the movement trajectories (can also be regarded as projected trajectories) on the horizontal plane (x-y plane) and perform a PCA (Principal Components Analysis) to extract the desired axis. In this experiment, the first principle component dimension was regarded as the mapping of the main motion dimension of the trajectories (marked as the new x-axis, x').

Therefore, the second principal component dimension, which was regarded as the dimension orthogonal to the main motion dimension (marked as the new y-axis, y'), was the axis used to measure the interference effect for the vertical waving condition (illustrated in Figure 4.2). Through manual inspection, PCA could be applied to 94.8% of the vertical waving trajectories to locate the desired axis. The desired axes of the rest of the trajectories were located manually.

The behaviour synchrony between the robot and the participants in this experiment was measured by the information distance synchrony detection method introduced in Chapter 3 using information distance value.

4.2.3 Results and Analysis

Motor Interference Analysis

For both motor interference analysis and motor coordination analysis, a 2 (congruency, referred as congruency of observed movements and performed movements, within subjects variable) * 2 (direction, referred as the participants' waving direction, within subjects variable) * 2 (music, referred as the presence of music, within subjects variable) * 2 (age, referred as the age group, between subjects variable) mixed ANOVA was performed to investigate the impact of these four factors on eliciting the interference effect. In addition, a repeated-measures 2 (congruency) * 2 (direction) * 2 (music) ANOVA was performed to further investigate the impact of these three variables in different age groups respectively. Paired t-tests with Bonferroni corrections were used between appropriate pairs of conditions as follow-up tests. The effect size was measured by Eta-Squared in the ANOVA tests and by Cohen's d in the paired t-tests. For an effect that was approaching significance, additional information of Observed Power was provided. For claiming statistical significance, the significance level of an effect should be less than or equal to 0.05. For claiming 'approaching' statistical significance, the significance level of an effect should be at least less than .1 (for the paired t-tests, it was further required that the significance level should be less than .15 after Bonferroni corrections).

In the 2*2*2*2 mixed ANOVA test, no significant differences were found between the standard deviation for the congruent condition and the standard deviation for the incongruent condition. A significant main effect of direction was found, $F(1, 22) = 5.392$, $p = .030$, $\eta = .197$. No other effect was found significant in this analysis, Fs(1, 22) < 2.600, ps > .121, ηs < .106. The significant main effect of direction is illustrated in Figure 4.3.

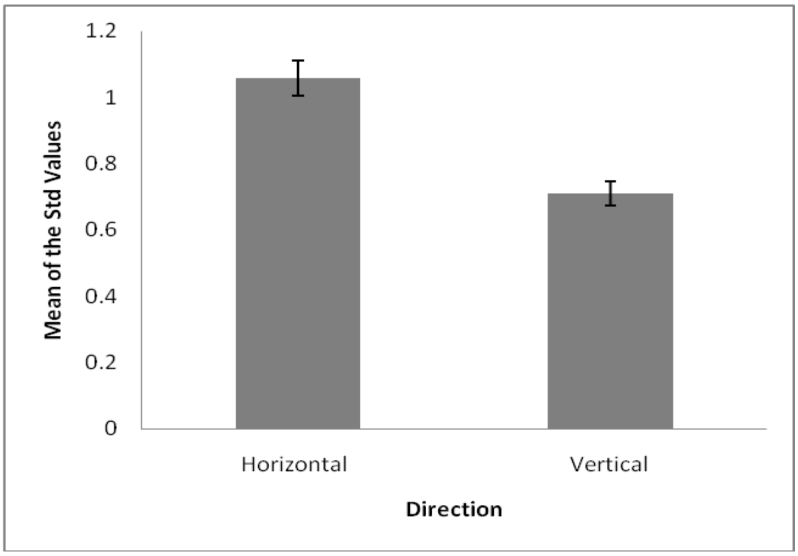


Figure 4.3: Mean of the standard deviation values for horizontal waving movements and vertical waving movements of the participants.

In order to further investigate the effect of congruency, which was the main interest of this experiment, the follow-up t-tests were performed to contrast the congruent movement variances and the incongruent movement variances across different conditions (horizontal waving with music, horizontal waving without music, vertical waving with music and vertical waving without music). Please note that, in the follow-up t-tests of the 2*2*2*2 mixed ANOVA test, the samples for each condition included both the adult samples and child samples. The results indicated that the movement variances for the incongruent condition was significantly greater than the congruent condition when the participants were waving vertically and the music was switched on, $t(23) = 3.533$, $p = .002$ (corrected $\alpha = .0125$), Cohen's d = .721 but insignificant for the rest of the conditions, $ts(23) < 1.545$, ps > .136, Cohen's d s < .315, (corrected $\alpha = .0125$). The t-test results are illustrated in Figure 4.4.

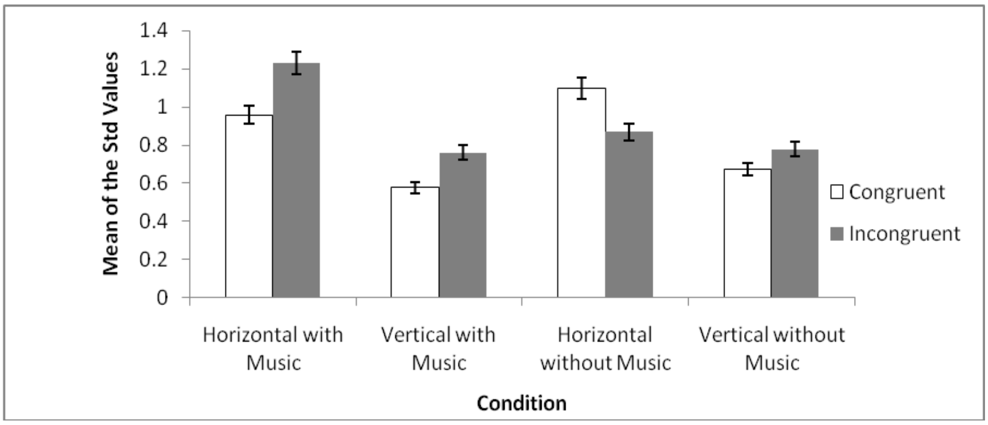
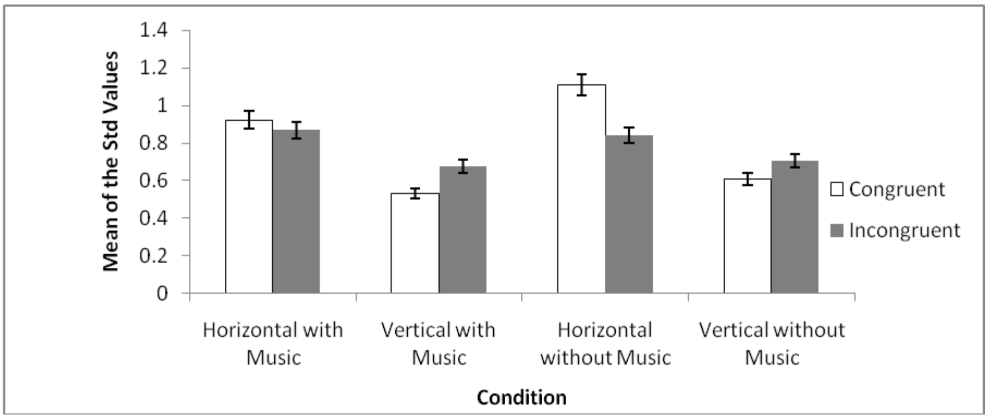
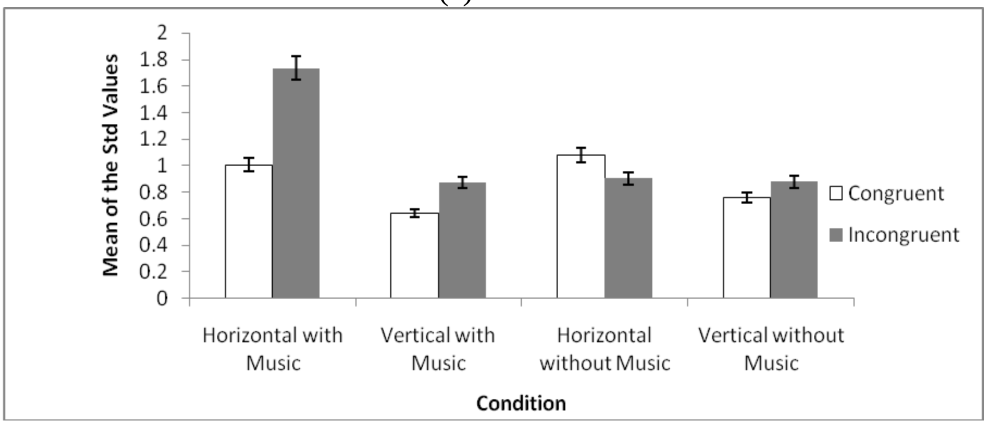


Figure 4.4: Mean of the standard deviation values for performed movements of the participants during observation of KASPAR2 performing congruent and incongruent movements in different conditions (horizontal waving with music, horizontal waving without music, vertical waving with music and vertical waving without music).

In the subsequent repeated-measures 2*2*2 ANOVA tests performed in both adult and child age groups, no effect was found significant in either of the two tests, *F*s(1, 13) < 2.507, *p*s > .137, *η*s < .162 for the adult age group and *F*s(1, 9) < 2.884, *p*s > .124, *η*s < .243 for the child age group. Although the main effect of direction was not significant in these two tests, the trend of this effect was in-line with the results from the 2*2*2*2 mixed ANOVA test. That is, the mean of the standard deviation for the horizontal condition was higher than the mean of the standard deviation for the vertical condition for both child and adult age group.



(a) Adults



(b) Children

Figure 4.5: Mean of the standard deviation values for performed movements of the participants (part *a* for adult participants and part *b* for child participants) during observation of KASPAR2 performing congruent and incongruent movements in different conditions (horizontal waving with music, horizontal waving without music, vertical waving with music and vertical waving without music).

In the follow-up t-tests performed in the two age groups, the results of these t-tests and the previous t-tests were generally in-line with each other. These results suggested that the difference between congruent and incongruent condition was approaching significance only for the vertical waving with music condition in both the adult age group, $t(13) = 2.526$, $p = .025$ (corrected $\alpha = .0125$), Cohen's d = .675, Observed Power = .647, and the child age group $t(9) = 2.440$, $p = .037$ (corrected $\alpha = .0125$), Cohen's d = .771, Observed Power = .585. For the rest of the conditions, the difference between congruent and incongruent condition was found not significant, $ts(13) < 1.062$, $ps > .307$ (corrected $\alpha = .0125$), Cohen's d < .284 for the adult age group and $ts(9) < 1.812$, $ps > .103$ (corrected $\alpha = .0125$), Cohen's d < .574 for the child age group. These t-test results are illustrated in Figure 4.5.

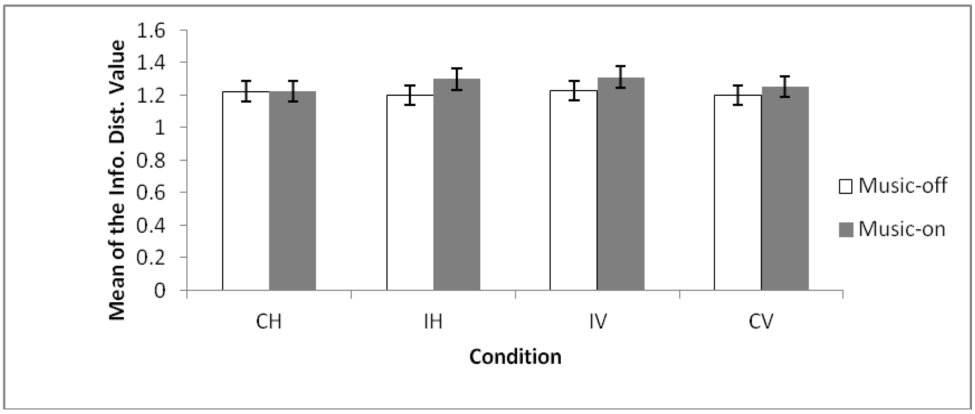


Figure 4.6: Mean of the information distance values for performed movements of the participants when the music was on and off for four different conditions in Experiment I. Please note different letters stand for different conditions (C: congruent movement, I: incongruent movement, H: horizontal waving, V: vertical waving).

Motor Coordination Analysis

In the 2*2*2*2 mixed ANOVA test, three interaction effects were found significant: direction * age, $F(1, 22) = 6.723$, $p = .017$, $\eta = .234$; congruency

* direction * age, $F(1, 22) = 29.889$, $p < .001$, $\eta = .576$; and congruency * direction * age * music, $F(1, 22) = 4.850$, $p = .038$, $\eta = .181$. No other effect was found significant, $Fs(1, 22) < 2.530$, $ps > .126$, $\eta s < .103$.

As the effect of music was one of our main interests in motor coordination analysis, follow-up paired t-tests with Bonferroni corrections were performed to contrast the information distance level when the music was on and the information distance level when the music was off across different conditions (horizontal waving and observing congruent movements, vertical waving and observing congruent movements, horizontal waving and observing incongruent movements, vertical waving and observing incongruent movements) to further investigate the impact of music. The paired t-test results indicated that no significant difference was found between the mean information distance value of the music-on condition and the mean information distance value of the music-off condition, $t(23) < 1.814$, $p > .083$ (corrected $\alpha = .0125$), Cohen's d < .370. These t-test results are illustrated in Figure 4.6.

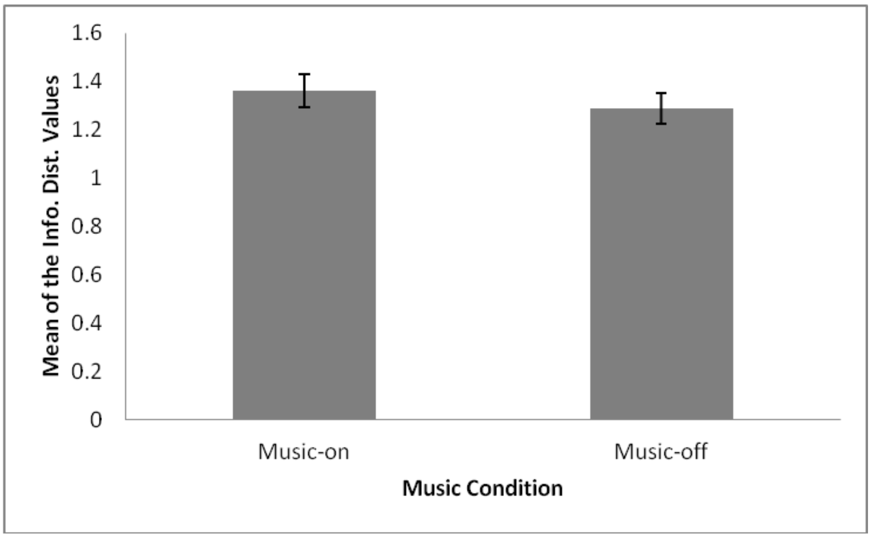


Figure 4.7: Mean of the information distance values for performed movements of the adult participants for music-on and music-off conditions.

In the subsequent repeated-measures 2*2*2 ANOVA test performed in the adult age group, the main effect of music was found approaching significant, $F(1, 13) = 4.492$, $p = .054$, $\eta = .257$, Observed Power = .501. The mean information distance value for the music-off condition tended to be significantly lower than the mean information distance value for the music-on condition (illustrated in Figure 4.7). In addition, the differences between the mean information distance value for the horizontal waving condition and the mean information distance value for the vertical waving condition was found approaching significance (illustrated in Figure 4.8), $F(1, 13) = 3.600$, $p = .080$, $\eta = .217$, Observed Power = .420.

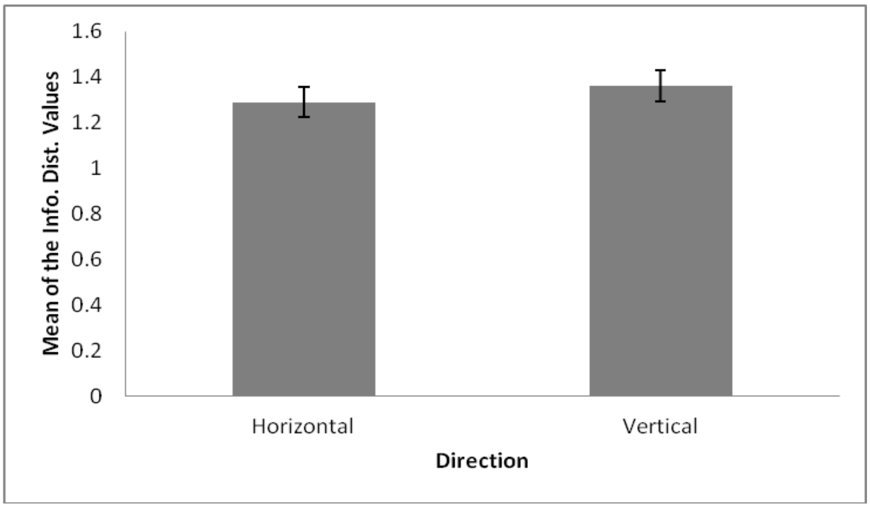


Figure 4.8: Mean of the information distance values for performed movements of the adult participants when they were waving horizontally and vertically.

Apart from the two approaching significant main effects, two two-way interaction effects were found significant in this test: congruency * music, $F(1, 13) = 4.954$, $p = .044$, $\eta = .276$, and congruency * direction, $F(1, 13) = 19.635$, $p = .001$, $\eta = .602$. The congruency * music interaction effect is illustrated in Figure 4.9. The results indicated that the movements of the adult participants and the humanoid robot were more synchronized in congruent condition than in incongruent condition when the music was on, and the situation became the opposite when the music was off. The congruency * direction interaction effect is illustrated in Figure 4.10 (a), which suggested that the movements performed by the adult participants and the humanoid robot were more synchronized for incongruent condition than for congruent condition when the adult participants were waving horizontally, and the situation became the opposite when the adult participants were waving vertically. No other effect was found significant in this test, $Fs(1, 13) < 2.737$, $ps > .122$, $\eta s < .174$

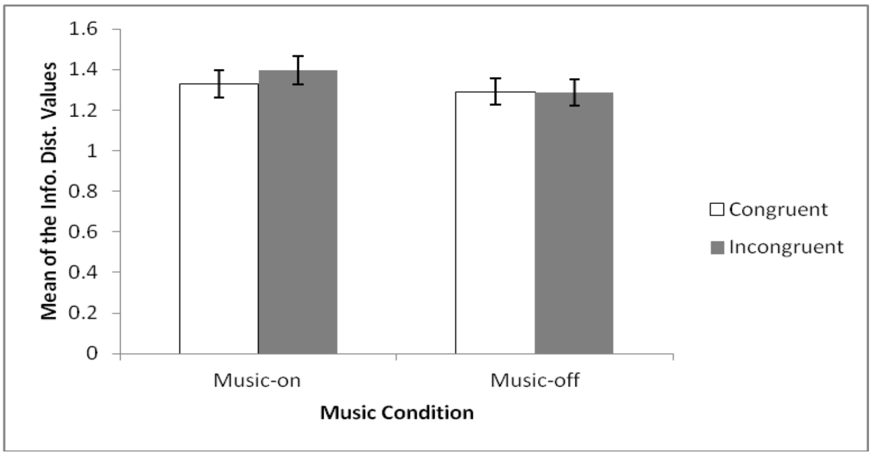
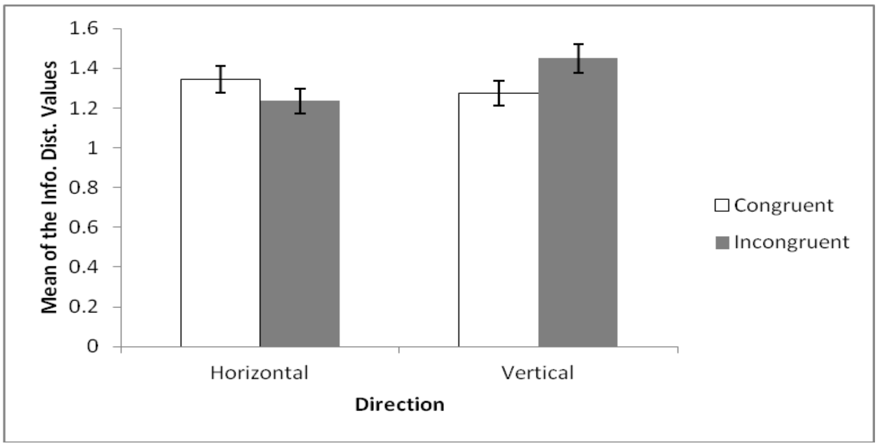
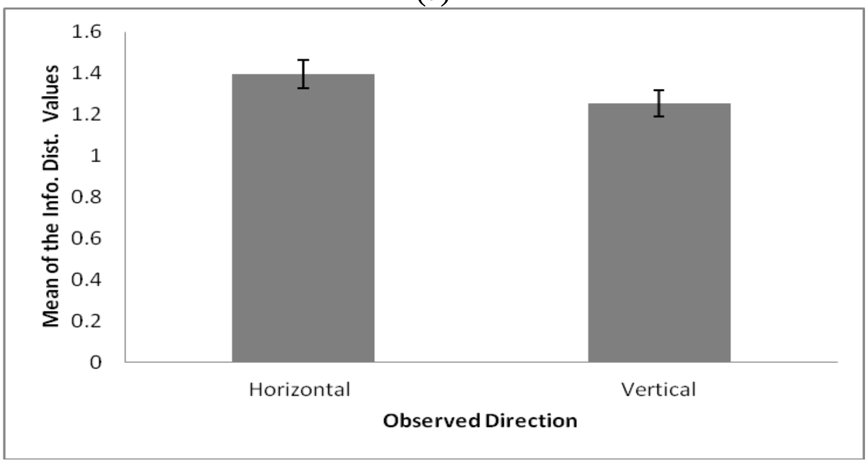


Figure 4.9: Mean of the information distance values for performed movements of the adult participants during observation of the humanoid robot performing congruent and incongruent movements for music-on and music-off conditions.

An alternative and possibly clearer explanation to the congruency * direction interaction could be given by rearranging the variables used in the ANOVA test from a different perspective: change the variables from congruency * direction * music to ‘observed direction’ (i.e. the robot’s movement direction) * direction * music (Stanley et al. 2007). Consequently, the previous interaction effect of congruency * direction could be replaced by a single main effect, observed direction. Meanwhile, the previous main effect of congruency was replaced by an interaction effect of observed direction * direction.



(a)



(b)

Figure 4.10: (a) Mean of the information distance values for performed movements of the adult participants during observation of the humanoid robot performing congruent and incongruent movements for horizontal waving condition and vertical waving condition in Experiment I. (b) alternative explanation of figure (a): mean of the information distance values for performed movements of the adult participants during observation of the humanoid robot performing horizontal movements and vertical movements in Experiment I.

Therefore, the significant interaction effect of congruency * direction introduced earlier became a significant main effect of observed direction, which indicated that the movements of the adult participants and the humanoid robot were more synchronized when the robot was performing vertical movements than the robot was performing horizontal movements. This part of the result is illustrated in Figure 4.10 (b). Please

Note that the observed direction effect is automatically used to replace the congruency * direction interaction effect in the rest part of this chapter in order to present the results in a more intuitive manner.

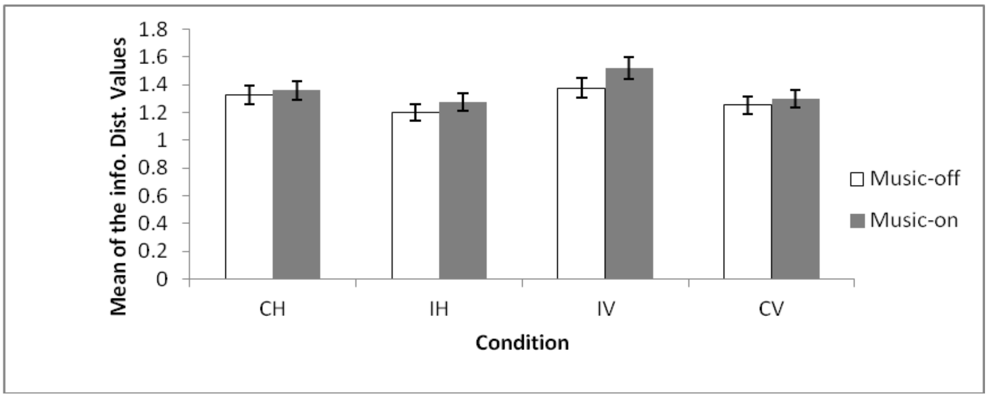


Figure 4.11: Mean of the information distance values for performed movements of the adult participants when the music was on and off for four different conditions in Experiment I. Please note different letters stand for different conditions (C: congruent movement, I: incongruent movement, H: horizontal waving, V: vertical waving).

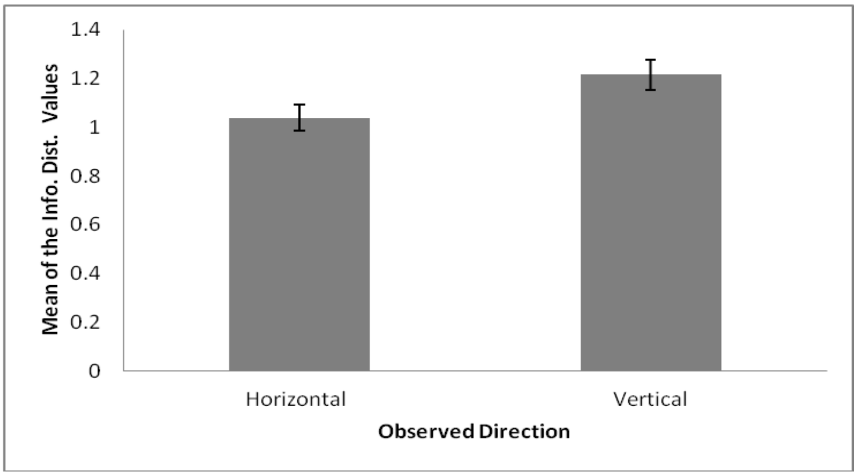


Figure 4.12: Mean of the information distance values for performed movements of the child participants during observation of the humanoid robot performing horizontal movements and vertical movements in Experiment I.

Table 4.2: this table summarizes all the significant and approaching significant effects found in Experiment I of chapter 4. In this table, the 'Level' column indicates the significance level of a particular effect (S: significant, A: approaching significant). In the follow-up t-tests, each letter represents a condition (C: congruent, I: incongruent, H: horizontal, V: vertical, M: with music, N: without music). Please note that the interaction effect of congruency * direction can be replaced with the main effect of observed direction.

Analysis Type	**Statistical Analysis**	**Test Type**	**Effect Name**	**Level**
Motor Interference	***2*2*2*2 ANOVA***	***Main test***	Direction	S
		Follow-up test	CVM/ IVM	S
	2*2*2 ANOVA (Adult group)	***Follow-up test***	CVM/ IVM	A
	2*2*2 ANOVA (Child group)	***Follow-up test***	CVM/ IVM	A
Motor Coordination	***2*2*2*2 ANOVA***	***Main test***	Direction* Age	S
			Congruency* Direction* Age	S
			Congruency* Direction* Music* Age	S
	2*2*2 ANOVA (Adult group)	***Main test***	Direction	A
			Music	A
			Congruency* Direction	S
			Congruency* Music	S
		Follow-up test	IVM/ IVN	A
			IHM/ IHN	A
	2*2*2 ANOVA (Child group)	***Main test***	Congruency* Direction	S
			Congruency* Direction* Music	A

In the follow-up t-tests, the difference between the mean information distance value for the music-on condition and music-off condition approached significance, when the adult participants and the robot were performing incongruent movements: $t(13) = 2.410$, $p = .031$ (corrected $\alpha = .0125$), Cohen's d = .644, Observed Power = .606 for participants vertical waving condition and $t(13) = 2.415$, $p = .031$ (corrected $\alpha = .0125$), Cohen's d = .646, Observed Power = .606 for participants horizontal waving condition.

For both conditions, the mean information distance value of the music-on condition was higher than the mean information distance value of the music-off condition, which indicated that the movements of the adult participants and the humanoid robot tended to be more synchronized when the music was off. The t-test results are illustrated in Figure 4.11.

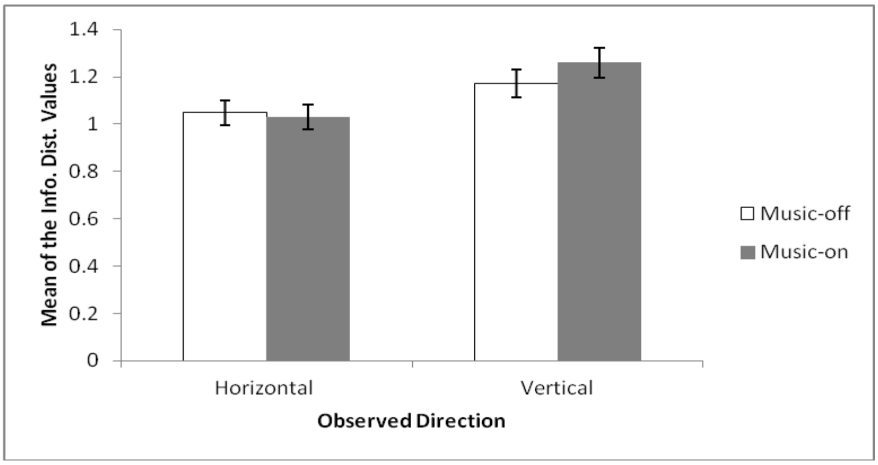


Figure 4.13: Mean of the information distance values for performed movements of the child participants during observation of the humanoid robot performing horizontal and vertical movements in music-on and music-off conditions in Experiment I.

In the 2*2*2 repeated-measures ANOVA test for the child age group, a significant main effect of observed direction was found: $F(1, 9) = 11.278$, $p = .008$, $\eta = .556$. Contrary to what was in the adult age group, the movements of the child participants and the humanoid robot were more synchronized when the robot was performing horizontal movements than the robot was performing vertical movements (illustrated in Figure 4.12).

In addition, a two-way interaction effect was found approaching significance: observed direction * music, $F(1, 9) = 4.183$, $p = .071$, $\eta = .317$, Observed Power = .447. This interaction effect suggested that the movements of the child participants and the humanoid robot were more synchronized when the music was on than the music was off for the condition they were observing the robot performing horizontal movements, and the situation tended to become the opposite when they were observing the robot performing vertical movements (illustrated in Figure 4.13). No other effect was found significant for the child age group in this test, $F\text{s}(1, 9) < 3.347$, $p\text{s} > .101$, $\eta\text{s} < .271$. All significant and approaching significant effects are summarized in table 4.2.

4.2.4 Discussion of Results

In the motor interference analysis, the significant main effect of participants’ waving direction was in-line with similar findings presented in other studies (Kilner et al. 2003, Oztop et al.2005 and Stanley et al. 2007). These results indicated human participants behaved differently when they waved their arms in different directions.

There was no significant main effect of congruency found in the motor interference analysis. However, the follow-up t-test results suggested that significant interference effect could be found when the participants were waving vertically with the music turned on. It is interesting to investigate why motor interference was only elicited in this condition. The impact of music might be a possible explanation although there was no significant effect found for the music factor in motor interference analysis.

In the 2*2*2*2 mixed ANOVA test, the mean of the movement variances for the congruent condition was greater than the incongruent condition when the music was off and the mean of the movement variances for the congruent condition was smaller than the incongruent condition when the music was on (illustrated in Figure 4.14). Although the interaction effect of congruency and music was not significant in this ANOVA test: $F(1, 22) = 2.600$, $p = .121$, $\eta = .106$, Observed Power = .338, it was much closer to significant than other in-significant effects in that test: $Fs(1, 22) < 1.702$, $ps > .206$, $\eta s < .072$. In addition, the movement variances for the vertical waving condition were significantly smaller than the movement variances for the horizontal waving condition.

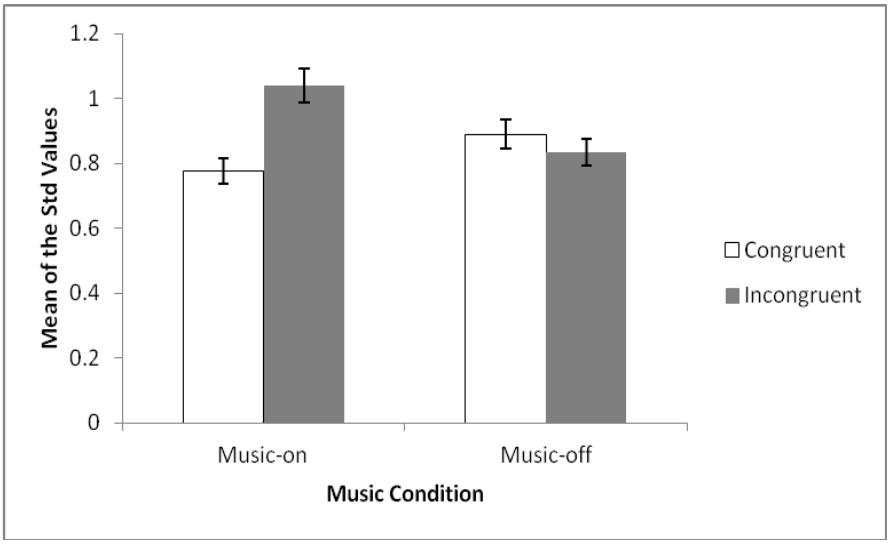


Figure 4.14: Mean of the standard deviation values for performed movements of the participants during observation of the humanoid robot performing congruent and incongruent movements in music-on and music-off conditions in Experiment I.

Therefore, the influence to the movement variance amount between music-on and music-off conditions had a greater impact to the vertical waving condition than to the horizontal waving condition and might consequently facilitate the interference effect. It is noteworthy that the significant interaction effect of congruency * music found in the adult age group in motor coordination analysis was in-line with this explanation. The findings of this experiment so far were not enough to draw a solid conclusion what role the impact of music might play in eliciting the interference effect. However, these results at least implied that the usage of music in this experiment might influence elicitation of the interference effect to a certain degree. Further research is needed to investigate the impact of the music on motor interference in human-humanoid interaction.

Regardless of what factor actually elicited the interference effect, its presence in this experiment might indicate that motor interference can be elicited in the interaction with a humanoid robot without a biological motion profile. On the other hand, the fact that no interference effect was found for the music-off condition suggested the non-biological motion humanoid robot alone might not be sufficient to provoke the interference effect.

In the motor coordination analysis, an approaching significant main effect of music was found in the adult age group. Contrary to our expectation, the mean information distance value for the music-on condition was lower than the music-off condition, which indicated that the movement of the participants and the humanoid robot tended to be more synchronized when the music was off. The follow-up t-test results (illustrated in Figure 4.11) were in-line with this finding. From video inspection and the feedback from the participants, it was found that this phenomenon was very likely sourced from the expectation of the participants. In this experiment, the participants were completely naïve about the purpose of this experiment and they had no idea what behaviour the humanoid robot was capable of in the experiment. Some participants might have higher expectation for KASPAR2 for the music-on condition than the music-off condition. That is, they might expect KASPAR2 to exhibit more skills or intelligence when the music was on. Therefore, these participants started to wave faster or slower intentionally to see whether the robot might change its behaviour.

Consequently, their movements were less synchronized with the humanoid robot. Hence, the experimental results of this study might not deliver the real impact of music on motor coordination. Further experiments are required to investigate the influence of music to motor coordination.

The difference between age groups was not found significant in either the motor interference analysis or the motor coordination analysis. The results might suggest that the children and the adults treated the humanoid robot in a similar manner in this experiment.

A further statistical analysis of information distance value showed that the rhythm of the participants' waving behaviour was synchronized with the rhythm of the humanoid robot in over 81% of the trials (if the average information distance value of one trial was below 1.5, the movements of the participants and the humanoid robot were considered as generally synchronized in that trial. The threshold of 1.5 was an empirical value obtained from practical human-humanoid interaction). As stated earlier, the participants were not instructed to wave in a particular rhythm or to imitate the robot during the experiment, instead, they were instructed to decide their own movement rhythm. Therefore, this statistical analysis result suggested that the participants might be affected by the humanoid robot's behaviour rhythm in the human-humanoid interaction and adapt to it, which supported the findings in Robins et al.'s study (Robins et al. 2008).

4.3 Experiment II

4.3.1 Introduction

The second experiment reported in this chapter was designed to further investigate a few areas that were not covered in the first experiment, including the effect of human participants' beliefs on human-humanoid interaction as well as comparing human-humanoid interaction with interactions between a human and other agents.

The first objective of this experiment was to clarify whether the human participants' beliefs could facilitate the interference effect in human-humanoid interaction based on the similar experimental settings adopted in experiment I. This objective was mainly inspired by Stanley et al.'s study (Stanley et al. 2007). The results of their study suggested that participants' beliefs about the origin of the moving dot stimuli had a significant impact on their behaviours. Motor interference could be elicited even when the moving dot stimulus did not have a biological motion profile, if the participants believed that the moving dot trajectories were generated from human movements (more details please refer to Chapter 2, section 2.3.2). In experiment I, the interference effect had been found in the interaction between a human and a humanoid robot without biological motion profile. It was possible that the impact of music might play an important role in eliciting the interference effect. In experiment II, the effect of music and age group was removed from the experiment, instead, additional instructions similar to the agency instruction adopted in Stanley et al.'s work were used to investigate the effect of human participants' beliefs. The instructions used in this experiment were named as the 'engagement' instructions. The words 'engaged' and 'engagement' of a robot here meant that the participants were informed that the robot they were observing was also observing the participants' behaviours but it could not react as it had its own fixed behaviour patterns. This implied to the participants that the robot was able to observe others' behaviours, which might be regarded as a biological feature by the participants. Hence, the first issue to be explored in experiment II was whether an interference effect could be elicited if human participants believed that they were interacting with a humanoid robot that was 'engaged' in the human-humanoid interaction although it did not have biological motion. If the participants' beliefs of the 'engagement' of the robot in human-humanoid interaction were critical in facilitating the elicitation of an interference effect, it would be hypothesized that the interference effect should be found under the engaged condition but not under the other conditions.

The second objective of this experiment was to extend our investigation concerning motor coordination. In experiment I, participants tended to coordinate their behaviours to the humanoid robot's behaviour rhythm in their interactions with the humanoid robot. However, whether other visual stimuli, such as a virtual moving dot or a mechanical pendulum, could also elicit human participants' motor coordination in the same experimental setting as that of the humanoid robot had not been investigated. Thus, the motor coordination investigation was carried out simultaneously with the motor interference investigation. In this experiment, the participants' behaviours in their interaction with the three different types of visual stimuli were compared and analyzed to evaluate the influence of different types of visual stimuli on the participants' behaviours. Moreover, the impact of participants' beliefs of the 'engagement' of the robot on motor coordination was also studied.

4.3.2 Experimental Design

Participants

Twenty-four right-handed adult participants participated in the experiment. They were all students (undergraduate or postgraduate) or staff from the University of Hertfordshire and were naive with respect to the purpose of the experiment.

Visual Stimuli

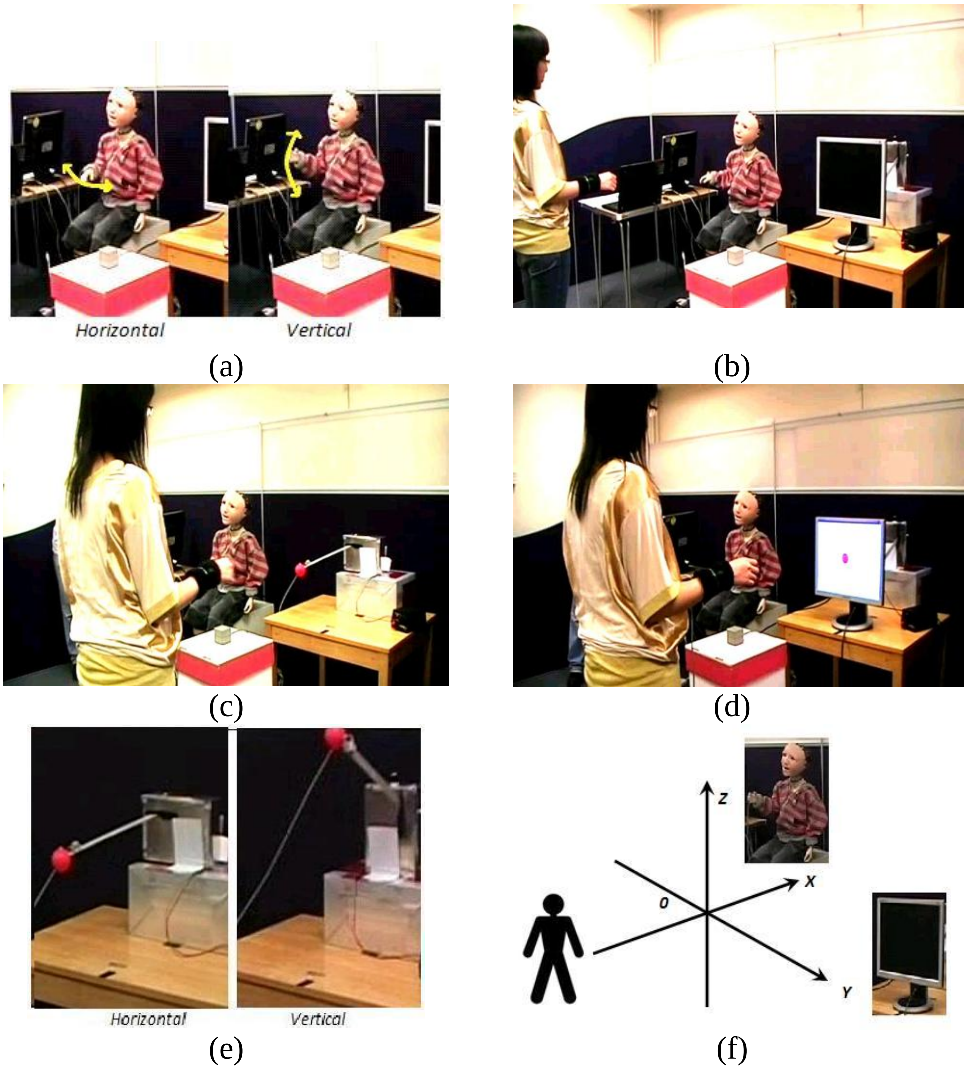


Figure 4.15: (a) Illustrations for KASPAR2's movements; a participant was instructed to stand at two different positions when he/she was interacting with different visual stimuli, one position for KASPAR2 and the other for the pendulum and the moving dot: (b) a participant interacting with KASPAR2; (c) a participant interacting with the pendulum (d) a participant interacting with a computer generated moving dot (the pre-specified positions of the pendulum and the moving dot screen were marked on the wooden table using black plastic strips to enable quick switching of the equipment); (e) illustrations for pendulum movements, horizontally (left) and vertically (right); (f) illustration for the x-y-z reference frame used in the experiment layout.

Three different types of visual stimuli (a humanoid robot, a mechanical pendulum and a virtual moving dot) were used in this experiment (shown in

Figure 4.15). All of these stimuli were designed to have constant speed motion profiles and approximately the same amplitude (approximately 30 cm) and frequency settings. Every complete back and forth wave movement (left to right then left again) of the visual stimuli took approximately 2.35 seconds (time differences between different stimuli were less than or equal to 7%).

All three visual stimuli were placed 1 meter away from the participants. Participants were asked to look at a particular focus point of each of these stimuli, namely KASPAR2's waving hand, a red ball on the end of the pendulum arm and the virtual moving dot displayed on the LCD screen. Each of these focus points were located at approximately the same height. The settings were intended to provide the participants with comparable visual perception of different visual stimuli.

The humanoid robot used in this experiment, KASPAR2 (illustrated in Figure 4.15 (a), was the same humanoid robot used in experiment I. Please refer to section 4.2.1 for more details.

The pendulum (illustrated in Figure 4.15 (e)) was specifically built by our research team for the purpose of this experiment. It was 31 cm in length, the same length as KASPAR2's forearm. There was a 5-cm diameter red ball attached to the end of the pendulum arm to attract attention from the participants. The pendulum had a 12V DC permanent magnetic motor with inline gearbox, which was connected to a 1.5 AMP regulated DC power supply with six adjustable voltage levels ranging from 1.5V to 12V. In this experiment, the voltage level was set to 3V. The pendulum could be rotated to switch between horizontal movements and vertical movements.

The virtual moving dot stimulus (illustrated in Figure 4.15 (d)) was computer generated and presented on a 17 inch monitor. The dot stimulus was red on a white background. The size of the dot was comparable with the size of the ball used on the pendulum. The screen of the LCD monitor could be rotated to switch between horizontal movements and vertical movements.

Waving Behaviour

The participants were required to only wave horizontally despite the visual stimuli movement direction. In experiment II, each participant was required to participate in six trials (three visual stimuli * congruent/incongruent conditions). The duration of the experiment would have had to be doubled, if the vertical waving behaviour had also been introduced. Based on the previous experience from experiment I, there might be a risk that participants lost their concentration if the number of the experimental trials was further extended and as a result, the accuracy of the experimental results might be affected. Therefore, a single waving behaviour direction was introduced to the participants. According to Kilner et al.’s work (Kilner et al. 2003) and Stanley et al.’s work (Stanley et al. 2007), horizontal arm movements tended to elicit more significant interference effects compared to vertical arm movements. However, in experiment I, it had been only found an interference effect in the vertical waving condition instead of the horizontal waving condition. Therefore, it was more interested in looking for the interference effect in horizontal waving condition and decided to choose the horizontal waving behaviour ahead of the vertical waving behaviour in experiment II. The basic waving behaviour introduced in experiment I was retained in this experiment: the upper arm of a subject remained still and the subject waved only the forearm horizontally.

Data Collection

The magnetic motion tracking system used in experiment II was the same system used in experiment I. One point worth mentioning was the movement trajectories of the virtual moving dot could not be collected with the motion tracking system, as it was not physically embodied. A computer program was therefore developed to simulate the trajectories of the virtual moving dot and the results of the simulation were recorded.

Procedure and Instruction

The general procedure of experiment II was similar to that of experiment I. During the experiment, each participant was required to participate in six trials (three visual stimuli * two congruency conditions), with the order of presentations counterbalanced across participants. Each trial lasted around 30 seconds and each participant was instructed to concentrate on the visual stimuli's focus point and wave his/her arm within each trial.

Compared with the instructions used in experiment I, there were two main differences in the instruction given to the participants in experiment II. The first change was in order to avoid the problem stated in section 4.2.4 (i.e. some of the participants might assume that if they changed their waving speed or rhythm, KASPAR2 would also change its behaviour). The participants were informed that the visual stimuli only moved in fixed patterns and as such would not adjust its movements according to the participants' behaviours.

The second change was to add the 'engagement' instructions. When the participants were interacting with KASPAR2, half of the participants were informed by the experimenter that they were interacting with a humanoid-robot that was 'engaged' in the interaction by telling them, "KASPAR2 is watching your movements, however, it will not respond to your behaviours this time" (engaged instruction group). The other half of the participants were informed that they were interacting with a humanoid-robot that was not 'engaged' in the interaction by saying, "KASPAR2 isn't really watching you, therefore, it will not respond to your behaviours this time" (not-engaged instruction group). The rest of the instructions were identical for all participants.

Measurement

The possible interference effects were quantified by the standard deviation of the movement trajectory positions within the plane orthogonal to the dominant movement dimension. In this experiment, the participants only waved horizontally. Therefore, the x-y plane was the dominant movement plane and only the coordinates in the z-dimension were used to measure the interference effect.

In experiment I, the standard deviation of the z coordinates of the entire trial were calculated for each trial and for each participant (referred to as trial-scale measure). In the present experiment, the second measurement scale, segment-scale measure was introduced. Segment-scale measure was widely used in other studies in the related areas (Kilner et al. 2003, Oztop et al. 2005, Bouquet et al. 2007 and Stanley et al. 2007). By adopting the segment-scale measure, the results of this experiment were more comparable with other studies. In the segment-scale measure, the trajectories of the participants were segmented off-line (that is, each movement from left-most position to right-most position was counted as one segment, and vice versa). For each segmented movement, the standard deviation of the z coordinates was calculated. The mean of these standard deviation values was then calculated across all movement segments for each trial and for each participant. In this experiment, different participants were allowed to wave at different waving speeds. Consequently, some participants might produce more movement segments than others during a fixed time trial. Therefore, only the first fifteen movement segments (excluding the movement segments at the start and the end of each trial, which might be particularly long or short) of each trial were used in the analysis to maintain an equivalent sample size of movement segments for each trial. It was chosen to use fifteen movement segments for each trial to ensure the movement segments of all participants could be equally analyzed.

Compared with segment-scale measure, the trial-scale measure might provide a more general picture of the data distribution for each trial as it utilized all the data for each trial. Both measurement scales were adopted in experiment II as supplement to each other.

The measurement for motor coordination in experiment II was same as the measurement used in experiment I. That is, motor coordination was measured by the information distance value.

4.3.3 Results and Analysis

For both motor interference analysis and motor coordination analysis, a repeated-measures 2 (congruency of observed movements and performed movements) * 3 (visual stimuli type) ANOVA wass performed. In addition, a 2 (congruency of observed movements and performed movements, within subjects variable) * 2 (engagement instruction group, between subjects variable) mixed ANOVA was performed to further investigate the impact of the engagement instruction group when the participants were interacting with the humanoid robot. Paired t-tests with Bonferroni corrections were used between appropriate pairs of conditions as follow-up tests. The effect size was measured by Eta-Squared in the ANOVA tests and by Cohen's d in the paired t-tests. For an effect that was approaching significance, additional information of Observed Power was provided.

Motor Interference Analysis – Segment-scale Measure

In the 2*3 ANOVA test, a significant main effect of congruency, $F(1, 23) = 8.448$, $p = .008$, $\eta = .269$ was found (illustrated in Figure 4.16). On average, the standard deviation for the congruent condition was lower than the standard deviation for the incongruent condition regardless of the visual stimuli type. No other significant effect was found in this analysis, $Fs(1, 22) < .631$, $ps > .541$, $\eta s < .054$. In the follow-up tests, it was found that the difference between the standard deviation for the incongruent condition and the standard deviation for the congruent condition approached significance when the participants were observing KASPAR2's movements, $t(23) = 2.300$, $p = .031$ (corrected $\alpha = .017$), Cohen's d = .471, Observed Power = .598. No significant difference was found when the participants were observing the movements of the pendulum, $t(23) = 1.759$, $p = .092$ (corrected $\alpha = .017$), Cohen's d = .359, or the virtual moving dot, $t(23) = 1.576$, $p = .129$ (corrected $\alpha = .017$), Cohen's d = .321. These results suggested that the movement interference effect was only approaching significance in the interaction between the participants and the humanoid robot.

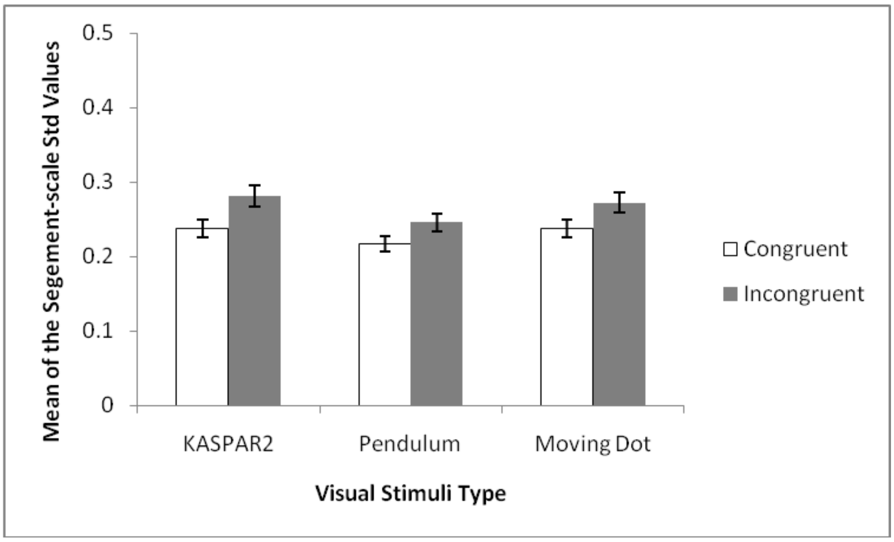


Figure 4.16: Mean of the segment-scale standard deviation values for performed movements of the participants during observation of three different types of visual stimuli performing congruent and incongruent movements

The 2*2 mixed ANOVA test indicated a significant main effect of congruency, $F(1, 22) = 5.260$, $p = .032$, $\eta = .193$ (illustrated in Figure 4.17), which was in-line with the approaching significance interference effect found in the above test. There was no other significant effect found, $Fs(1, 22) < .874$, $ps > .360$, $\eta s < .038$.

In a further follow-up t-test, it was found that the difference between the congruent condition and the incongruent condition for the engaged instruction group approached significance, $t(11) = 1.976$, $p = .074$ (corrected $\alpha = .025$), Cohen's d = .571, Observed Power = .438. The difference between the congruent condition and the incongruent condition for the not-engaged instruction group was not significant, $t(11) = 1.178$, $p = .264$ (corrected $\alpha = .025$), Cohen's d = .340. The standard deviation for the incongruent conditions was higher than the standard deviation for the congruent conditions for both engaged instruction group and not-engaged instruction group

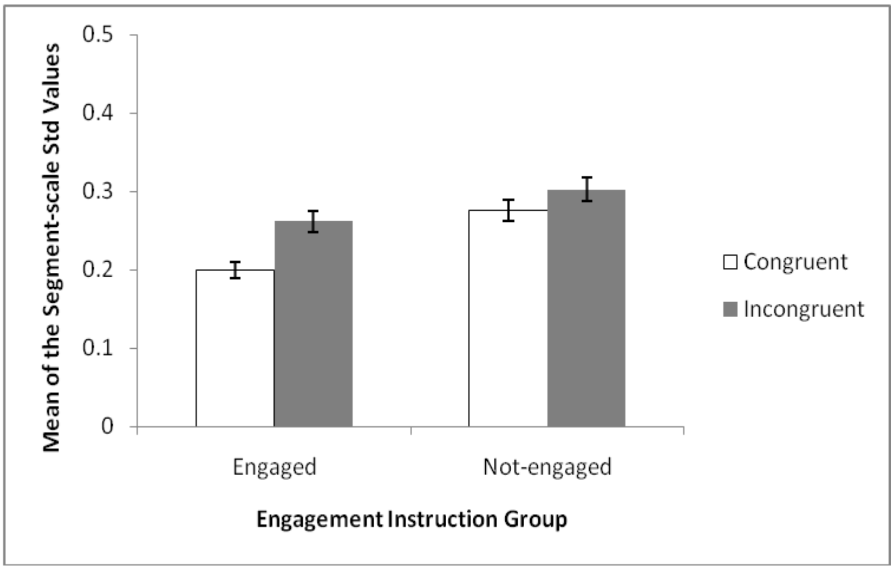


Figure 4.17: Mean of the Segment-scale standard deviation values for performed movements of the participants during observation of KASPAR2 performing congruent and incongruent movements in Engaged and Not-Engaged conditions.

Motor Interference Analysis -- Trial-scale Measure

In the 2*3 ANOVA test, none of the main effect or interaction effect was found significant, Fs(1, 23) < .1.262, ps > .303, ηs < .103. In the follow-up t-tests, the results were similar to the results in the segment-scale measure analysis. Difference between the standard deviation for the congruent condition and the incongruent condition was found approaching significance when the participants were observing KASPAR2's movements, $t(23) = 2.333$, $p = .029$ (corrected $\alpha = .017$), Cohen's d = .476, Observed Power = .608. There was no significant effect found in the other two types of visual stimuli, i.e. the pendulum, $t(23) = .944$ $p = .355$ (corrected $\alpha = .017$), Cohen's d = .193, or the virtual moving dot, $t(23) = .831$, $p = .414$ (corrected $\alpha = .017$), Cohen's d = .170. The results of the paired t-tests are illustrated in Figure 4.18.

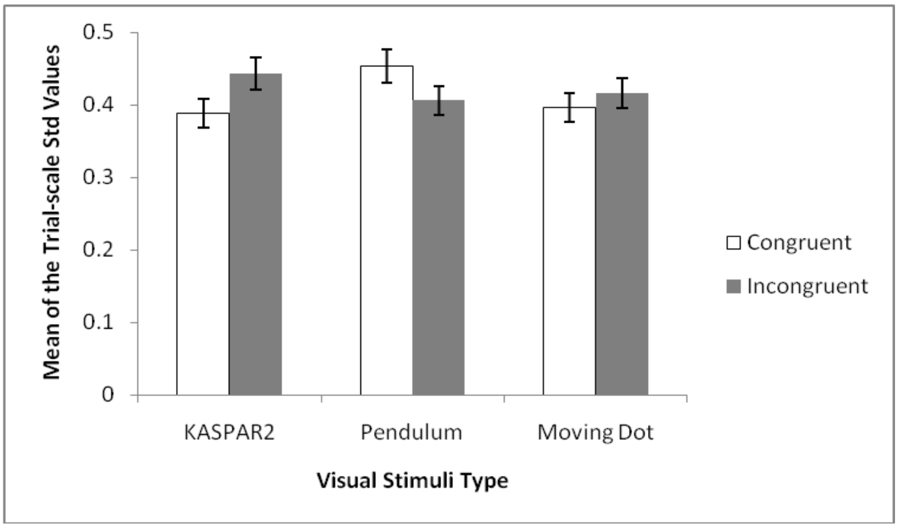


Figure 4.18: Mean of the Trial-scale standard deviation values for performed movements of the participants during observation of three different types of visual stimuli performing congruent and incongruent movements.

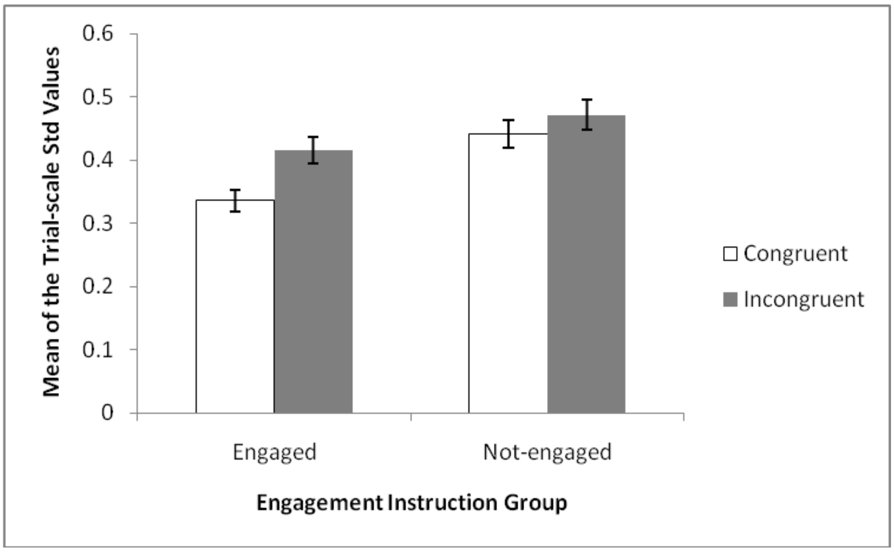


Figure 4.19: Mean of the trial-scale standard deviation values for performed movements of the participants during observation of KASPAR2 performing congruent and incongruent movements in Engaged and Not-Engaged conditions.

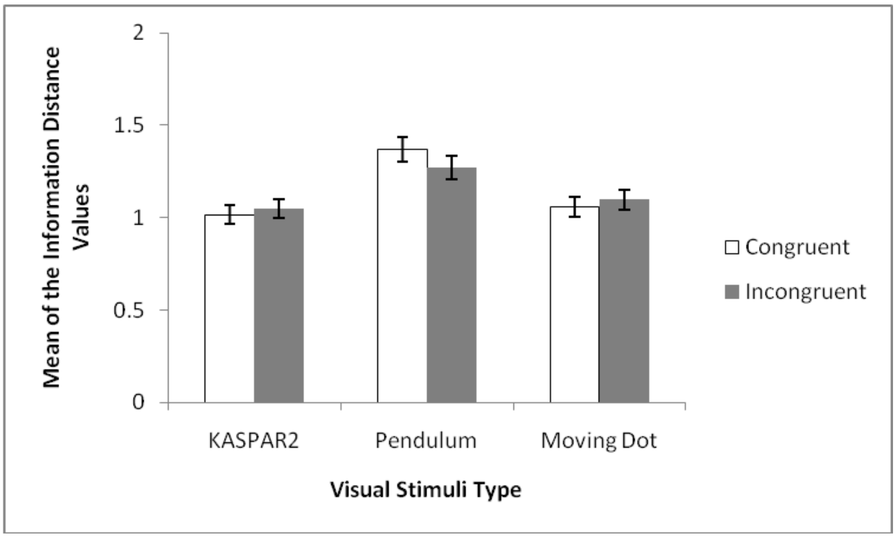


Figure 4.20: Mean of the information distance values for performed movements of the participants during observation of three different types of visual stimuli performing congruent and incongruent movements.

In the 2*2 mixed ANOVA test, there was a significant main effect of congruency, $F(1, 22) = 5.466$, $p = .029$, $\eta = .199$ (illustrated in Figure 4.19). It confirmed the previous finding in the similar ANOVA test using segment-scale measure. No other significant effect was found, *F*s(1, 22) < 1.094, *p*s > .307, *η*s < .047.

In the further follow-up t-tests, the difference between the standard deviation for the incongruent condition and the congruent condition for the engaged instruction group approached significance, $t(11) = 2.484$, $p = .030$ (corrected $\alpha = .025$), Cohen's d = .717, Observed Power = .620, but not for the not-engaged instruction group, $t(11) = .882$, $p = .396$ (corrected $\alpha = .025$), Cohen's d = .254.

Motor Coordination Analysis

The 2*3 ANOVA analysis indicated a significant effect of visual stimuli type, $F(1, 22) = 7.039$, $p = .004$, $\eta = .39$ (illustrated in Figure 4.20). However, no other significant effect was found in this analysis, *F*s(1, 22) < 2.501, *p*s > .105, *η*s < .185.

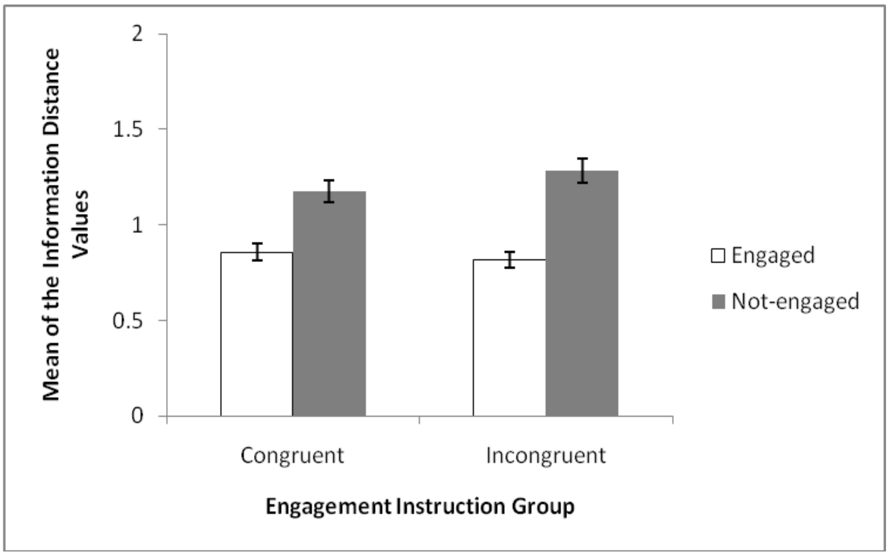


Figure 4.21: Mean of the information distance values for performed movements of the participants during observation of KASPAR2 performing congruent and incongruent movements in Engaged and Not-Engaged conditions.

In the follow-up tests, the mean information distance value of the pendulum condition was significantly greater than the mean information distance value of the KASPAR2 condition, $t(23) = 4.413$, $p < .001$ (corrected $\alpha = .009$), Cohen's d = .901, and the virtual moving dot condition, $t(23) = 3.523$, $p = .002$ (corrected $\alpha = .009$), Cohen's d = .719, for the congruent condition. For the incongruent condition, the difference between the KASPAR2 condition and the pendulum condition was found approaching significant $t(23) = 2.405$, $p = .025$ (corrected $\alpha = .009$), Cohen's d = .491, Observed Power = .634.

In the 2*2 mixed ANOVA analysis, a significant main effect of engagement, $F(1, 22) = 4.456$, $p = .046$, $\eta = .168$, was found (illustrated in Figure 4.21). A two-way interaction between congruency and engagement instruction group approached significance, $F(1, 22) = 3.426$, $p = .078$, $\eta = .135$, Observed Power = .425.

Follow-up t-tests showed that for the incongruent condition, the mean information distance value for the not-engaged instruction group tended to be significantly higher than the mean information distance value for the engaged instruction group, $t(11) = 2.802$, $p = .017$ (corrected $\alpha = .0125$), Cohen's d = .809, Observed Power = .723. For the congruent condition, the difference between the mean information distance value for the not-engaged instruction group and the engaged instruction group also approached significance, $t(11) = 2.086$, $p = .061$ (corrected $\alpha = .0125$), Cohen's d = .602, Observed Power = .477. No significant effect was found between the congruent condition and the incongruent condition, $ts(11) < 1.698$, $ps > .118$ (corrected $\alpha = .0125$), Cohen's ds < .491.

Table 4.3: this table summarizes all the significant and approaching significant effects found in Experiment II of chapter 4. In this table, the 'Level' column indicates the significance level of a particular effect (S: significant, A: approaching significant). In the follow-up t-tests, each letter represents a condition (C: congruent, I: incongruent, K: KASPAR2, P: pendulum, V: virtual moving dot, E: engaged instruction group, N: not-engaged instruction group).

Analysis Type	**Statistical Analysis**	**Test Type**	**Effect Name**	**Level**
Motor Interference (Segment sale)	***2*3 ANOVA***	***Main test***	Congruency	S
		Follow-up test	KC/ KI	A
	2*2 ANOVA	***Main test***	Congruency	S
		Follow-up test	EC /EI	A
Motor Interference (Trial scale)	***2*3 ANOVA***	***Follow-up test***	KC/ KI	A
	2*2 ANOVA	***Main test***	Congruency	S
		Follow-up test	EC /EI	A
Motor Coordination	***2*3 ANOVA***	***Main test***	Equipment	S
		Follow-up test	KC/ PC	S
			VC/ PC	S
			KI/ PI	A
	2*2 ANOVA	***Main test***	Engagement	S
			Congruency* Engagement	A
		Follow-up test	EI/ NI	S
			NC/ NC	A

4.3.4 Discussion of Results

The significant and approaching significant effects in the results of experiment II are summarized in Table 4.3. In the motor interference analysis, significant main effect of congruency was found in the 2*2 ANOVA test for both segment-scale measure and trial-scale measure. Moreover, in the follow-up tests of the 2*3 ANOVA test, approaching significant difference was found between the standard deviation for the incongruent condition and the standard deviation for the congruent condition when the participants were observing the movements of the humanoid robot for both segment-scale measure and trial-scale measure.

These results suggested that the interference effect tended to be significant when the participants were observing KASPAR2's movements. For the pendulum and the virtual moving dot, no evidence was found for the emergence of an interference effect. In the further investigation of the impact of the engagement instruction, it was found in both segment-scale measure and trial-scale measure that the interference effect tended to be significant for the engaged instruction group. In contrast, no interference effect was found for the not-engaged instruction group. This part of the results might imply a tendency that the difference between the congruent condition and incongruent condition for the engaged instruction group had more contribution to the significance of the overall interference effect for the humanoid robot condition than the difference between the congruent condition and incongruent condition for the not-engaged instruction group. The experimental settings concerning human-humanoid interaction in experiment I were almost identical to the experimental settings adopted in experiment II except the application of music and the engagement instruction. In experiment I, no significant or approaching significant interference effect was found for horizontal waving condition despite the music condition. These results together suggested that the belief of the participants about the engagement of the robot had at least an important impact, if not critical, on eliciting the interference effect in this experiment.

The non-biological motion moving dot stimuli in this study did not provoke an interference effect, as expected. Compared with the studies that found significant interference effect with a non-biological moving dot (Stanley et al. 2007, Bouquet et al. 2007 and Kilner et al. 2007), it was noticeable that all these studies involved more or less human factors inside their experiments. Bouquet et al.'s study and Kilner et al.'s study both adopted human experimenters as a part of the visual stimuli. In Stanley et al.'s work, although the authors did not adopt human experimenters in their second experiment, human-related instructions were given to the participants as agency instructions. The participants might have inferred a possible source of these abstract moving dots based on the visual stimuli they had experienced or the instructions that they had been given. Therefore, it was possible that the participants in these previous studies made assumptions that these moving dots were generated by a human and this assumption might have facilitated the elicitation of an interference effect. In the present experiment, no human-related factor was introduced to the participants. Instead, the presence of the robot and the mechanical pendulum might have led the participants to infer that the moving dot was generated using a mechanical approach or a computer. As expected, the mechanical pendulum did not provoke any interference effect. This might be due to its explicitly non-biological appearance, which was comparable to the mechanical arm in Kilner et al.'s experiment (Kilner et al. 2003). In that experiment, the mechanical arm did not elicit an interference effect either.

The findings about the motor interference presented in this study do not necessarily conflict with the previous findings about the importance of bottom-up effects and biological motion in human-robot interaction. In neither experiment I nor II of this thesis, the non-biological motion humanoid robot, KASPAR2, alone did not elicit any interference effect. The experimental conditions that significant or approaching significant interference effects were found all had certain additional factors introduced, namely the music or the participants' beliefs. The individual features such as the participants' beliefs, music, bottom-up effects and biological motion profile may supplement with each other instead of conflicting with each other when they are applied to human-humanoid interaction. These features may all potentially contribute to the overall perception of a robot as a 'social entity'. In this thesis, 'overall perception' refers to the human observer's overall perceptions of the robot in terms of appearance, motion, observers' beliefs and environmental features as related to a 'social entity' (i.e. an entity one can interact with socially). Please note that the precondition of this hypothesis is to stay on the 'left-hand side' of the "uncanny valley" (Mori 1970). For more details about the "uncanny valley", please refer to section 2.1.1. A robot with better overall perception might attract longer and more stable attention, which might consequently elicit an interference effect. Therefore, it is hypothesized that it may be the overall perception of a robot as a 'social entity' instead of any individual feature that is critical to elicit the interference effect in human-humanoid interaction.

The results of motor coordination analysis suggested that the preference of the participants to synchronize their movements with the humanoid robot was significantly higher than that with the mechanical pendulum. Although the differences of preference of the participants between the humanoid robot and the moving dot were not significant, the humanoid robot was still the most favoured visual stimulus according to average information distance values. The results concerning the engagement instruction group indicated that the participants tended to synchronize their movements with the humanoid robot better for the engaged instruction group than the not-engaged instruction group. These results of motor coordination analysis were also generally in-line with the hypothesis suggested concerning the robot's overall perception as a 'social entity' which might have caused the tendency that the participants preferred to synchronize their behaviours with an agent with better overall perception. Further research is required to validate this issue.

4.4 Conclusion

In this chapter, two experiments were performed to investigate both motor interference and motor coordination. In motor interference investigation, significant interference effect was found when the participants were interacting with a humanoid robot without biological motion profile. The participants' beliefs of the engagement of the robot and the application of music might both contribute to the overall perception of the humanoid robot and consequently provoke the interference effect in the two experiments respectively. In the motor coordination investigation, human participants were found tending to coordinate their behaviour rhythm to the behaviour rhythm of the humanoid robot. The overall perception of a robot may also facilitate motor coordination in human-humanoid interaction. Furthermore, the information distance synchrony detection method was successfully applied in the two experiments as an off-line behaviour synchrony measurement method, which further validated the effectiveness of this method.

Chapter 5
Real-time Behaviour Adaptation Using Information Distance

5.1 Introduction

The core objective of this thesis is to develop a method that enables a humanoid robot to adapt its behaviours to a human in real-time interaction. In order to realize this objective, the information distance synchrony detection method was developed to support the realization of the behaviour adaptation mechanism. In Chapter 3, the main principle, structure and the primary validation process of this method was presented. In Chapter 4, the information distance synchrony detection method was reported to be utilized in off-line motor coordination analysis for human-humanoid interaction. There is still one step to go to achieve the ultimate objective: realize the behaviour adaptation mechanism on a humanoid robot as well as validate the performance of the information distance synchrony detection method in real-time application.

In this chapter, a human-humanoid interaction experiment is reported with the information distance synchrony detection method adopted at real-time as the core part of a self-adaptation mechanism for a humanoid robot. Please note that the meaning of ‘adaptation’ in this chapter is specified to movement speed adaptation, which can also be regarded as motor coordination. The humanoid robot was expected to coordinate its movement speed to the human participants' movement speed in real-time interaction based on the synchrony information provided by the information distance method. If the motor coordination between a humanoid robot and a human participant could be successfully realized, it might enhance the social competence of the robot and consequently facilitate human-humanoid interaction.

The humanoid robot adopted in this experiment is the same robot used in the experiments reported in Chapter 4, KASPAR2 (please refer to section 4.2.1 for more details of this robot). Instead of simple arm waving behaviours, some more complex and more interesting interaction modes, such as speech and gesture, were introduced in this experiment to encourage the participants to get involved in the interaction with the robot. The instructions to the participants were given by KASPAR2's speech module instead of a human experimenter. The human experimenter only provided supplementary explanation when necessary.

During the experiment, human participants were instructed to interact with the humanoid robot by performing some fixed gesture patterns. Within their interaction, both the participants and the robot performed a selected pattern simultaneously. Meanwhile, the robot compared the movement synchrony between the participants and itself using the information distance method and adjusted its movement speed according to the calculated information distance values. Thus, the robot might gradually coordinate its own movements to match the participants' movements. In the actual experiment, there was also a baseline condition that the humanoid robot did not adapt its movements to the participants' movements. Instead, it always performed its movements using a constant speed. The experimental results and feedback of the participants for the adaptation condition and baseline condition were compared and analyzed to evaluate the impact of the behaviour adaptation mechanism. For the adaptation condition, the information distance value detected at the end of the human-humanoid interaction was expected to be significantly lower than the information distance value detected at the beginning of the interaction. It was also expected to find from the participants' feedback that most of the participants preferred the interaction with the humanoid robot for the adaptation condition than the interaction for the baseline condition

5.2 Experimental Design

Participants

Twenty-four right-handed participants participated in the experiment. Among these participants, eight of them were professionals; fifteen of them were undergraduate or postgraduate students from the University of Hertfordshire; the rest one was a secondary school student. All participants were naive with respect to the purpose of the experiment.

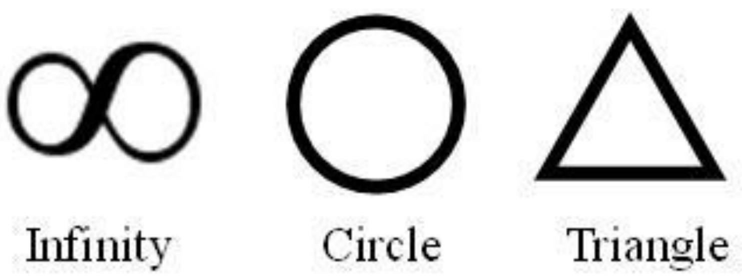


Figure 5.1: illustrates the movement patterns (infinity, circle and triangle) used in the experiment reported in Chapter 5.

Gesture Pattern

Three simple gesture patterns were adopted in the present experiment: infinity, circle and triangle (illustrated in Figure 5.1). The selected gesture patterns had two main attributes: simple and continuous. As this experiment was a preliminary attempt to realize behaviour adaptation in real-time human-humanoid interaction, the gesture patterns were designed to be relatively simple. During the experiment, both the participants and the humanoid robot needed to repeat performing the patterns several times continuously. Therefore, the continuity of the gesture patterns was a key feature to be taken into consideration. The patterns illustrated in Figure 5.1 all fully satisfied the above two requirements.

Speech Module

The speech function of the robot in this experiment was realized by playing pre-recorded sound wave files. These sound wave files were embedded in the main interaction program and played automatically at the appropriate time for the robot to give instructions to the participants. The sound wave files were produced by recording the output of a text-to-speech engine provided by the Acapela group (acapela-group.com 2010).

Gesture Interaction and Data Collection

In order to realize human-humanoid gesture interaction in this experiment, the gesture produced by the human participants needed to be captured, recorded and recognized so that the robot could make appropriate reactions to the participants' movements. To achieve this aim, some additional hardware equipment, software toolkit and library were employed.

In the experiment, the participants were required to use a Wii Remote (Sciencedaily.com 2008) to perform the gesture patterns (a Wii Remote is illustrated in Figure 5.2). A Wii Remote is a motion controller manufactured by Nintendo (Nintendo.co.uk 2010). It has an optical sensor and an acceleration sensor which enable it to be used as an accurate pointing device with the help of a Wii sensor bar (Castaneda 2006, Nintendo-europe.com 2011, Wisniowski 2006 and Wikipedia.org 2010). With appropriate software, one can operate a computer using a Wii Remote instead of a mouse.

In this experiment, a third party free software toolkit named ‘WiinRemote’ (onakasuita.org 2010) was applied as an interface between a Wii Remote and a computer. Through this toolkit, the participants’ arm movement trajectories could be mapped on to a computer’s screen as the movement trajectories of a mouse. In addition, operations to the digital buttons on the Wii Remote, such as the ‘A’, ‘B’, ‘+’ and ‘-‘ button, could be mapped as specified key inputs to the computer. In the present study, the ‘A’ button and ‘B’ button were mapped as the left button and the right button of a mouse respectively. Moreover, the ‘+’ button and ‘-‘ button were mapped as the ‘Y’ key (for yes) and ‘N’ key (for No) respectively to allow the participants to send confirmation information to the humanoid robot.

Figure 5.2: illustrates a Wii Remote motion controller. This figure is sourced from Wikipedia.org (Wikipedia.org 2010)

Apart from the WiinRemote toolkit, an open source pattern recognition library, AME Patterns library (Rajko 2008), was also utilized in the experiment to realize the gesture recognition function and a large part of the data collection function. The AME Patterns library provides an interface and background facilities for training and testing gesture patterns via mouse inputs. Its capacity for the trained patterns and tolerance to the user inputs were both adequate for this experiment. One point worth mentioning is when the gesture patterns were being trained and tested, each pattern was continuously repeated three times to increase the accuracy of the recognition of the gesture patterns. Consequently, every time the participants were instructed to perform a particular pattern during the interaction, they all needed to perform the gesture pattern continuously three times.

Figure 5.3: illustrates the experimental layout of the human-humanoid interaction experiment. A participant was holding a Wii Remote to perform a gesture pattern. The trajectories produced was projected onto the body of KASPAR2 using a projector.

If the participants could see the arm movement trajectories they left on the pattern recognition interface, they might have a better clue as to whether these trajectories matched the gesture pattern that they intended to perform. It was also important to make sure they did not move their attention away from the robot when they were observing their own arm movement trajectories because this was a human-robot interaction experiment and the participants were supposed to concentrate on the robot instead of a computer screen. Therefore, a projector was used to project the pattern recognition interface onto the body of the humanoid robot (illustrated in Figure 5.3), so that the participants could focus on the humanoid robot as well as observe their arm movement trajectories.

The original source code of the AME Pattern library was partially modified to embed the data collection function into the gesture recognition interface. The input from the Wii Remote, including the participants' arm movement trajectory data and the confirmation information, were collected and sent to the humanoid robot. These data were processed by the robot and then it could make appropriate reactions to the participants' behaviours in the human-humanoid interaction.

Procedure and Instructions

During the experiment, each participant was required to interact with the humanoid robot for three trials, one practice trial and two formal interaction trials. Within the two formal interaction trials, one was the adaptation trial that the robot might adapt its movement speed to match the participant's movement speed. The other was the baseline trial that the robot performed its arm movements in a constant speed regardless of the participant's movement speed. For each trail, the participants were asked to interact with the humanoid robot using all three gesture patterns one at a time in a pre-specified sequence. This sequence of application of the gesture patterns was counterbalanced across the participants.

Before starting the interaction, the humanoid robot introduced itself to the participants and gave instructions about how to use the Wii Remote to perform the gesture patterns. After the introduction, a practice trial was given to allow the participants to practise performing the gesture patterns. Within the practice trial, there was a cycle of interaction sessions. In each session, the participants were instructed by the robot to perform a gesture pattern that they wanted to practise. Once the participants finished performing the selected pattern, the pattern recognition program would identify the gesture pattern according to the movement trajectories produced by the participants. The robot then started to perform a pattern corresponding to the result output by the pattern recognition program and asked the participants whether the performed gesture pattern was correctly recognized. Afterwards, the participants should use the buttons on the Wii Remote to make a selection. If the participants chose ‘Yes’, the robot would respond with verbal encouragement and terminate the current interaction session; if the participants chose ‘No’, the robot would prompt the participants to try again. The practice trial lasted three minutes and the above interaction cycle persisted until the time limit was reached.

After the practice trial, the formal interaction trials then followed. The order of appearance of the adaptation trial and the baseline trial was counterbalanced across the participants. In each trial, there were three interaction sessions and each session consisted of four stages:

1. Pattern selection: the participant was instructed to select a gesture pattern for this interaction session according to the pre-specified sequence. The pattern selection procedure was similar to the procedure of the interaction session in the practice trial, which had been described above.

2. Robot movement speed demonstration: once the pattern was successfully selected and confirmed, the robot would

demonstrate its initial movement speed by re-performing the selected pattern with the initial movement speed.

3. Participant movement speed detection: after the second stage, the robot would invite the participants to perform the selected pattern together. Through this process, it could be detected that whether the robot was moving faster or the participants were moving faster in drawing the gesture pattern. The speed detection was realized by inspecting whether the participants completed performing the patterns before or after the robot completed performing the same patterns with the same starting time. If the participants completed first, it indicated that the participants were moving faster than and robot. If the robot completed first, it indicated that the participants were moving slower than the robot. With this information, the general direction of speed adaptation, i.e. whether the robot should increase or decrease its movement speed, in the adaptation interaction at the next stage could be set. This speed detection method was practical and easy to implement, which was suitable for a preliminary attempt to realize the behaviour adaptation mechanism in real-time human-humanoid interaction. As this method did not require real-time monitoring of the participants' movement speed, it could help to maintain the complexity of the whole system at a relatively low level, which could reduce the reaction time of the robot. Nevertheless, it also brought potential risk that the robot might not react properly if the consistency of the participants' movement speed was not well maintained. For example, if a participant performed the gesture patterns faster than the robot at this stage, the robot would take this information as a heuristic and prepare to move faster to match the

participant's speed at the next stage. However, at the next stage, this participant happened to perform the patterns slower than the robot. The robot would not realize this movement speed change without real-time movement speed monitor. Therefore it would stick with its previous plan to move faster. Consequently, the information distance results would indicate that the robot's movements and the participant's movements became less synchronized during the adaptation process as the robot was trying to adapt in a wrong direction. Thus, to avoid this situation, the participants were instructed to maintain their movement speed as consistant as possible in the next stage of the interaction. Apart from the previous instruction, the participants were particularly instructed to perform their movements either faster or slower than the robot's movement speed This instruction was to avoid the situation that the participants' movement speed was same as or very close to the robot's movement speed which would inhibit the adaptation mechanism functioning and might result in the effectiveness of the self-adaptation mechanism being unable to be fully tested.

4. Adaptation/non-adaptation interaction: the final stage was the only difference between the process of the adaptation trial and the baseline trial. At this stage, the participants were again invited by the robot to perform the selected gesture pattern together. The length of the interaction time of this stage was twice as long as that of the third stage. For the adaptation condition, the humanoid robot gradually increases or decreases its movement speed according to the general direction of speed adaptation obtained from the third stage until the information distance was reduced to a satisfaction limit or the time limit of

the interaction was reached. The empirical value of 1.5 adopted in the previous two experiments was continuously used as the satisfaction limit of this experiment. Various tests performed prior to the present experiment showed that this empirical value was also adequate for this task. Please be aware that the satisfaction limit might not always be reached due to the physical limitation of the robot's servos when some participants were moving extremely fast. In this case, the robot would stop increasing its movement speed when the maximum speed of the servos was reached and then maintain this movement speed until the end of the interaction. For the baseline condition, the humanoid robot maintained its initial movement speed without any change until the end of the interaction.

Measurements

In this experiment, there were three main quantities taken as the measurements. The first measurement was the first entry of the information distance value detected at the start of a human-humanoid interaction session for each pattern for each condition and for each participant (referred as *start-information value*). The second measurement was the last entry of the information distance value detected at the end of a human-humanoid interaction session for each pattern for each condition and for each participant (referred as *end-information value*). The third measurement was the mean of the information distance values calculated across each human-humanoid interaction session for each pattern for each condition and for each participant (referred as *mean-information value*). The effectiveness of the self-adaptation mechanism was mainly measured by whether the information distance value could be significantly reduced within the adaptation condition of the human-humanoid interaction. That is, the end-information value was expected to be significantly lower than the start-information value for the adaptation condition of the interaction. In addition, the end-information value and the mean-information value for the adaptation condition were expected to be significantly lower than those of the baseline condition. Please note that, according to the algorithm of the information distance synchrony detection method, each entry of the information distance value does not represent the movement synchrony between two agents at one particular time point but a period of time.

Questionnaire Design

Questionnaires are widely used as a tool to measure the users' perception of robots in Human-Robot Interaction research (Goetz et al. 2003, Kose-Bagci et al. 2010, Syrdal et al. 2007a). Due to the lack of commonly agreed standardized questionnaire, many researchers built their own questionnaires according to the requirements of their studies. Some effort has been devoted to the development of standardized questionnaires, such as the "Godspeed" series proposed by Bartneck et al.'s study (Bartneck et al. 2009), which were intended to be used to measure the anthropomorphism, animacy, likeability, perceived intelligence and perceived safety aspects of robots. Although it was a good start, there are still many aspects need to be covered in order to make this series of standardized questionnaires widely accepted. In the present study, a questionnaire was particularly developed to fit the requirement of this study. The participants were asked to fill this questionnaire after the experiment. The main questions of this questionnaire are listed below:

Q1: How well do you rate KASPAR2's gesture recognition?
Q2: How well do you rate KASPAR2's behaviour performance?
Q3: How would you rate KASPAR2 in terms of social interaction?

Q4: How much did you enjoy the game as a whole?

Q5: Which of the two games did you like better?

Question 1, 2, 3 and 4 were asked twice in the questionnaire for both the adaptation condition and the baseline condition. For these four questions, five-point Likert scale (Likert 1932) was used to enable the participants' feedback to be analyzed statistically. The participants were asked to give ratings to indicate their preference. The rating ranged from 1 to 5 (from 'Not good' to 'Very good' for Question 1 to Question 3 and from 'Not at all' to 'Very much' for Question 4). Question 5 was asked only once for the participants to select their preference between the two interaction conditions.

The development of the questionnaire employed in this work followed a few basic guidelines of questionnaire design, such as avoiding 'leading' questions, keeping the questionnaire short and succinct (Loughborough University 2013), not to over-decompose concepts (Bartneck et al. 2009), etc.. It was particularly important for this study to keep the questionnaire relatively short as the willingness of the participants to answer a long questionnaire was questionable especially after a long period time of interaction with a robot (Kiesler and Goetz 2002). The application of rating based feedback system might also encourage mindless responses when the participants were exhausted (Loughborough University 2013). Therefore, only five key questions were designed to inspect: 1) how accurate KASPAR2's gesture recognition was; 2) how well KASPAR2's movements were performed; 3) how sociable KASPAR2 were perceived to be; 4) how much did the participants enjoyed as a whole and 5) the participants' preference of the game.

5.3 Results and Analysis

Experimental Results Analysis

For the experimental results analysis, a repeated-measures 2 (adaptation condition) * 3 (gesture pattern type) ANOVA test with three different measurements (start-information value, end-information value and mean-information value) was performed. Paired t-tests with Bonferroni corrections were used between appropriate pairs of conditions as follow-up tests. The effect size was measured by Eta-Squared in the ANOVA tests and by Cohen's d in the paired t-tests. If there was an effect approaching significance, additional information of Observed Power would be provided.

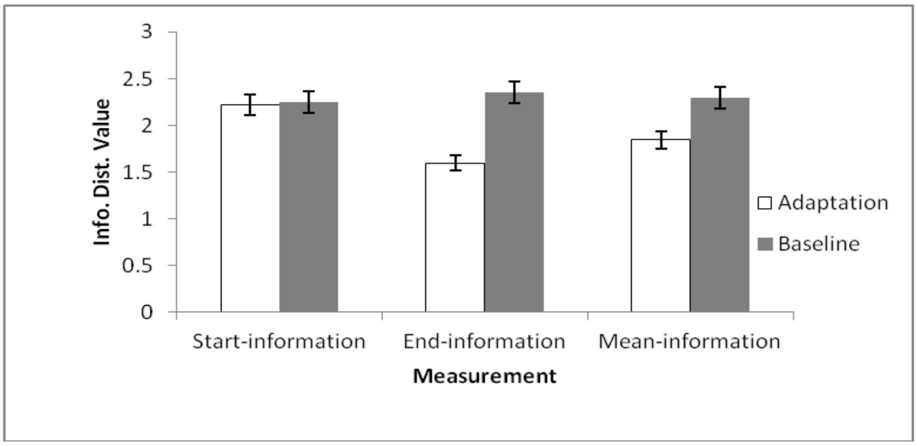


Figure 5.4: illustrates the start-information values, the end-information values and the mean-information values for the performed movements of the participants and the humanoid robot for the adaptation condition and the baseline condition of the interaction.

Significant main effects of adaptation were found for the end-information value, $F(1, 23) = 95.884$, $p < .001$, $\eta = .807$, and the mean-information value, $F(1, 23) = 42.504$, $p < .001$, $\eta = .649$, but not for the start-information value, $F(1, 23) = .076$, $p = .785$, $\eta = .003$ (illustrated in

Figure 5.4). In addition, significant main effects of pattern were found for all three measurements: $F(1, 22) = 4.795$, $p = .019$, $\eta = .304$ for the start-information value, $F(1, 22) = 8.274$, $p = .002$, $\eta = .429$ for the end-information value and $F(1, 22) = 8.432$, $p = .002$, $\eta = .434$ for the mean-information value (illustrated in Figure 5.5). The interaction effect of adaptation * pattern was not found significant for any of the three measurements, $F\text{s}(1, 22) < .335$, $p\text{s} > .719$, $\eta\text{s} < .030$, which indicated that the significant effects of adaptation were independent of the selection of gesture patterns.

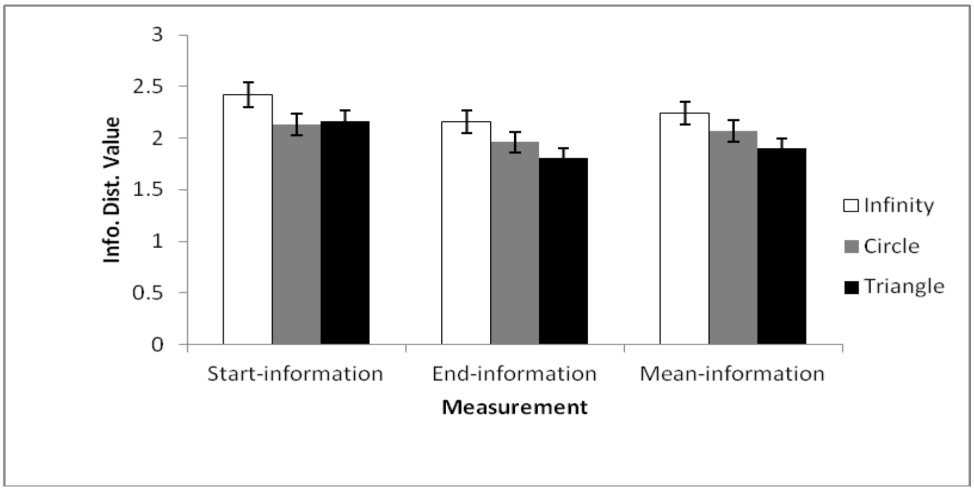
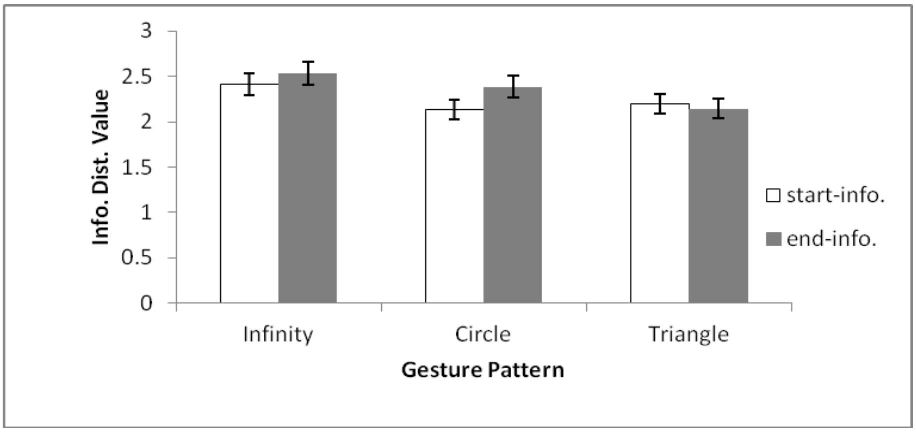


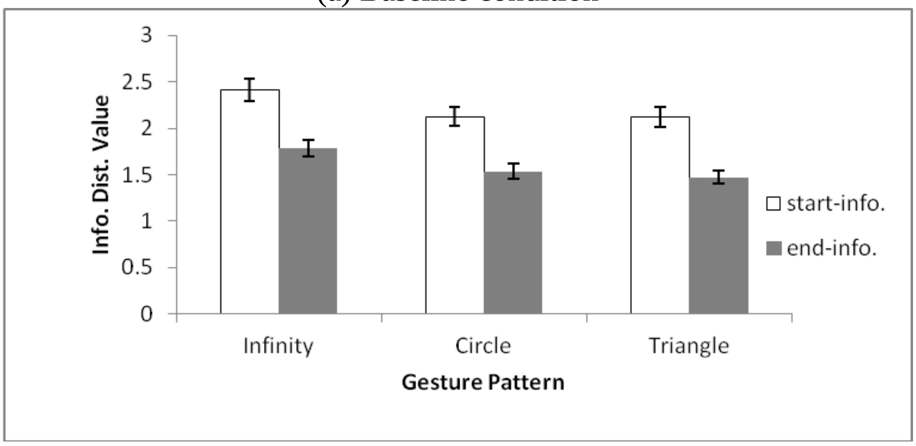
Figure 5.5: illustrates the start-information values, the end-information values and the mean-information values for the performed movements of the participants and the humanoid robot with different patterns (infinity, circle and triangle) in the interaction.

In order to further investigate the effectiveness of the self-adaptation mechanism, which was the core objective of this experiment, the follow-up paired t-tests were performed to contrast the start-information value and the end-information value for each gesture pattern and for both the adaptation condition and the baseline condition.

The results indicated that the end-information values were significantly smaller than the start-information values for all gesture patterns for the adaptation condition: *t*(23) = 4.278, *p* < .001 (corrected α = .017), Cohen's d = .873 for the infinity pattern, *t*(23) = 6.470, *p* < .001 (corrected α = .017), Cohen's d = 1.320 for the circle pattern and *t*(23) = 9.504, *p* < .001 (corrected α = .017), Cohen's d = 1.939 for the triangle pattern. However, no significant difference between the start-information value and the end-information value was found for any of the gesture pattern for the baseline condition, *t*s(23) < 2.160, *p*s > .041 (corrected α = .017), Cohen's ds < .441. The results of the paired t-tests are illustrated in Figure 5.6.



(a) Baseline condition



(b) Adaptation condition

Figure 5.6: illustrates the start-information values and the end-information values for the performed movements of the participants and the humanoid robot with different gesture patterns (infinity, circle and triangle) for the base-line condition and the adaptation condition of the interaction (part a for the base-line condition and part b for the adaptation condition)

Questionnaire Feedback Analysis

For the questionnaire feedback analysis, paired t-tests with Bonferroni corrections were used to compare the ratings given by the participants to question 1, 2, 3 and 4 for the adaptation condition and the participants' ratings to the same questions for the baseline condition. The effect size in these paired t-tests was measured by Cohen's d. If there was an effect approaching significance, additional information of Observed Power would be provided.

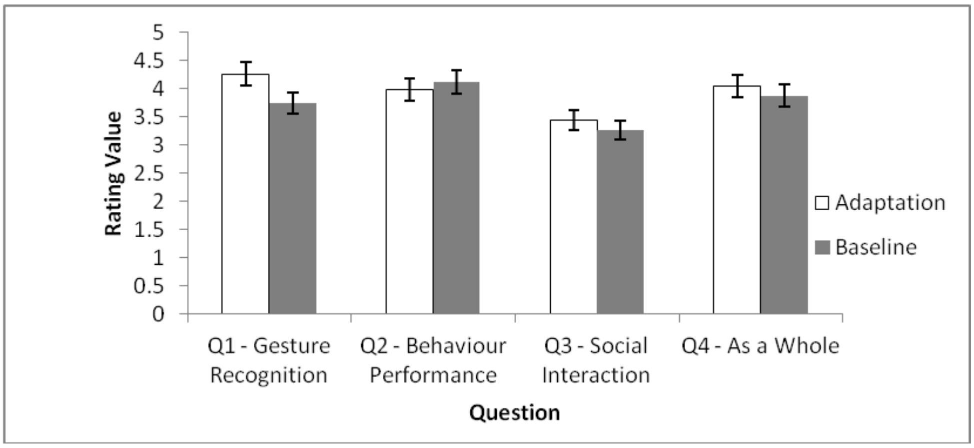


Figure 5.7: illustrates the ratings of the participants to Question 1, 2, 3 and 4 for both the adaptation condition and the baseline condition.

The results of the paired t-tests suggested that significant difference between the ratings of the participants for the adaptation condition and that for the baseline condition was only found in Question 1, $t(23) = 2.905$, $p = .008$ (corrected $\alpha = .0125$), Cohen's d = .593, but not for the rest of the three questions, $ts(23) < 1.446$, $ps > .162$ (corrected $\alpha = .0125$), Cohen's ds < .295. Those results are illustrated in Figure 5.7.

The significant and approaching significant effects found in both the experimental results and the questionnaire feedback are all summarized in Table 5.1.

Table 5.1: this table summarizes all the significant and approaching significant effects found in the experiment described in Chapter 5. In this table, the 'Level' column indicates the significance level of a particular effect (S: significant, A: approaching significant). Please note that the paired-t tests of the experimental results analysis were performed between appropriate pairs of the start-information values and the end-information values for three different patterns for the adaptation condition.

Analysis Type	**Test Type**	**Measurement Type**	**Effect Name / Condition Name**	**Level**
Experimental Results	***2*3 ANOVA test***	End-info.	Adaptation	S
		Mean-info.	Adaptation	S
		Start-info.	Pattern	S
		End-info.	Pattern	S
		Mean-info.	Pattern	S
	paired t-test	Start-info./ End-info.	Adaptation with Infinity pattern	S
		Start-info./ End-info.	Adaptation with Circle pattern	S
		Start-info./ End-info.	Adaptation with Triangle pattern	S
Questionnaire Feedback	***paired t-test***	Rating	Adaptation / Baseline	S
	Chi-square test	Preference	Adaptation / Baseline	S

For Question 5, 16 participants (66.7%) selected that they preferred to interact with KASPAR2 in the adaptation condition; 4 participants (16.7%) selected that they preferred to interaction with KASPAR2 in the baseline condition; the rest 4 participants (16.7%) did not have any preference or could not tell the difference between the adaptation condition and the baseline condition. The participants' preference according to the interaction type (adaptation / baseline) was statistically analyzed using a

Chi-square test. The result of the Chi-square test indicated that majority of the participants preferred the adaptation interaction, χ^2 (1) = 7.2, p = .007.

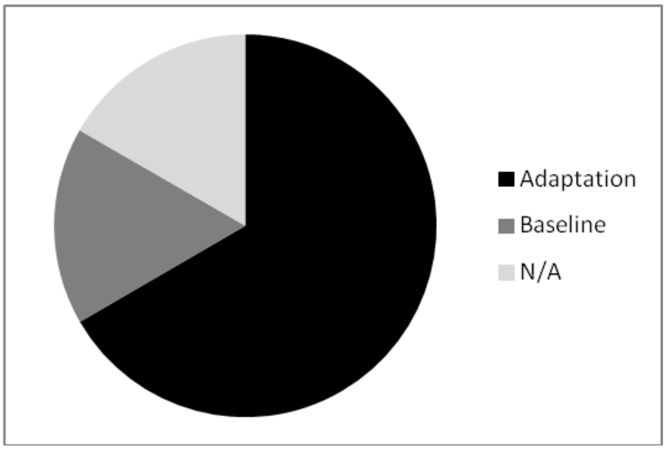


Figure 5.8: illustrates the preference of the participants in the interaction with KASPAR2 for the adaptation condition and the baseline condition.

5.4 Discussion of Results

In the 2 * 3 ANOVA test of the experimental results analysis, the end-information values and the mean-information values for the adaptation condition were found significantly lower than those for the baseline condition. No significant difference was found between the start-information values for the adaptation condition and the start-information values for the baseline condition. Moreover, the end-information values were found significantly smaller than the start-information values for the adaptation condition in the paired t-tests. However, the difference between the start-information values and the end-information values for the baseline condition was not found significant. Those results together indicated that the information distance level for the adaptation condition and the baseline condition was relatively close at the start of the human-humanoid interaction. During the interaction, the information distance level was significantly reduced for the adaptation condition but this kind of reduction was not found for the baseline condition. The change of the information distance level during the interaction between a participant and the humanoid robot for both the adaptation condition and the baseline condition was illustrated in Figure 5.9. Therefore, it could be inferred that the behaviour adaptation mechanism of the humanoid robot using the information distance method could successfully coordinate the robot's movement speed to the participants' movement speed in real-time human-humanoid interaction.

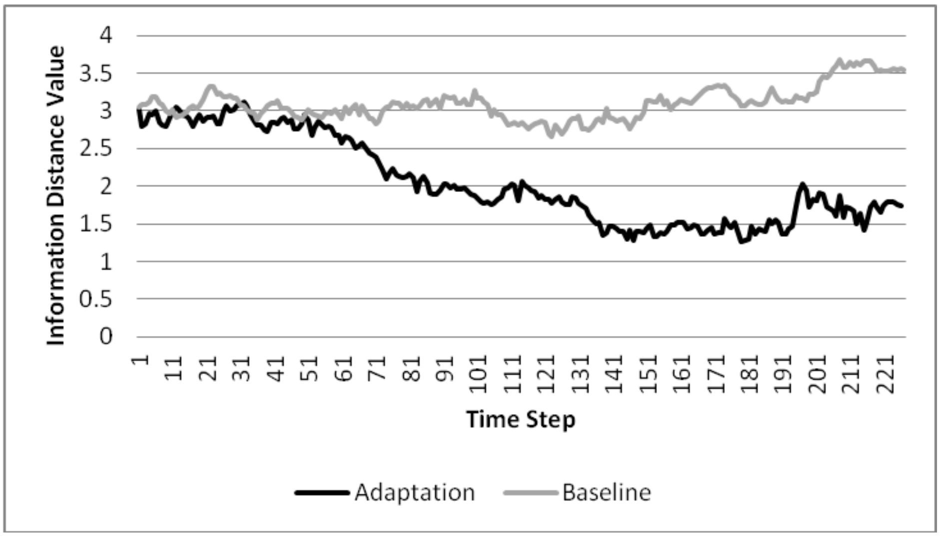


Figure 5.9: illustrates the change of the information distance level during the interaction between a participant and the humanoid robot for both the adaptation condition and the baseline condition. The gesture pattern used in those two interaction sessions was the circle pattern.

For the paired t-tests performed for the questionnaire feedback analysis, the difference between the participants' ratings for the adaptation condition and for the baseline condition was only found significant for question 1 (How well do you rate KASPAR2's gesture recognition?), but not for the rest of the three questions. The participants rated the performance of the gesture recognition function of the robot for the adaptation condition significantly higher than that for the baseline condition. Nevertheless, the gesture recognition module adopted for the adaptation condition and the baseline condition was completely identical. A possible explanation for this result was that the participants might be misled in the human-humanoid gesture interaction regarding the objective of this experiment. The reasons are listed as follows. First of all, the participants were naive about the purpose of this experiment. Secondly, the change of the movement speed during the interaction, due to the physical limitation of the robot's servos and the design of the adaptation program, was not very obvious for the participants to realize this process. Furthermore, the gesture recognition was one of the most important elements in this human-humanoid interaction experiment, which might leave a very deep impression on the participants. Consequently, the participants might infer that the purpose of this experiment was about testing the gesture recognition function of the humanoid robot. Therefore, when they were asked to rate the robot's gesture recognition for the baseline condition and the adaptation condition, they might leave a higher rating for the condition that they had better overall experience. This misunderstanding to the aim of the experiment might also affect the participants' ratings to the other three questions.

The results of Question 5 of the questionnaire (Which of the two games did you like better?), in which the majority of the participants preferred the interaction with the humanoid robot in the adaptation condition over the interaction with the humanoid robot in the baseline condition, was in-line with the above explanation. Moreover, the preference of the participants in Question 5 might suggest that the behaviour adaptation (could also be regarded as motor coordination in this experiment) mechanism using the information distance synchrony detection method successfully improve the social competence of the robot. Therefore, the expectation of realizing the behaviour adaptation mechanism on a humanoid robot was fulfilled for this experiment.

5.5 Conclusion

In this chapter, an experiment was performed to demonstrate the realization of a behaviour adaptation mechanism on a humanoid robot and investigate the effectiveness of this mechanism in real-time human-humanoid interaction. The results of the experiment indicated that the humanoid robot with the behaviour adaptation mechanism was capable of coordinating its behaviour to a human's behaviour. The information distance synchrony detection method was applied as the core part of the behaviour adaptation mechanism of the humanoid robot. The experimental results suggested that this method successfully guided the humanoid robot to coordinate its movement speed to match the participants' movement speed in real-time human-humanoid gesture interaction. The participants' feedback indicated that more participants preferred to interact with the humanoid robot with the motor coordination capability than the humanoid robot without this capability, which might suggest that the application of the behaviour adaptation mechanism increased the social competence of the humanoid robot.

Chapter 6
Summary

This chapter summarizes the experiments performed to address the proposed research questions and how the findings of these experiments respond to those research questions. Moreover, the contributions to knowledge are also summarized.

6.1 Summary of the Experiments

The three main experiments presented in this thesis are summarized as follows.

Experiment 1

In the first experiment, both motor interference and motor coordination in human-humanoid interaction were investigated. Participants of different age groups (adult / child) were instructed to interact with a child-size non-biological motion humanoid robot, KASPAR2, using arm waving behaviours. Within the actual experimental process, the participants were required to wave their arms either horizontally or vertically while observing congruent or incongruent movements preformed by the humanoid robot. There were 8 experimental conditions designed according to 3 variables: participants' arm movement direction (vertical / horizontal), behaviour congruency in human-humanoid interaction (congruent / incongruent) and the presence of the music effect (with music / without music). This experiment was designed using relatively playful and less constrained experimental settings. That is, the arm waving behaviour adopted was easier for the participants to produce (curvilinear instead of linear) and the movement rhythm of the participants was not restricted. The aim of the first experiment was to investigate under which circumstance the interference effect could be elicited as well as under which circumstance the participants' movement rhythm might be influenced by the robot's movement rhythm or the music rhythm.

Experiment 2

The second experiment was performed to further investigate the issues related to motor interference and motor coordination that were not covered in the first experiment. The experimental paradigm employed in experiment 2 was generally similar to the experimental paradigm used in experiment 1 in terms of the humanoid robot platform and the playful experimental settings. The differences between the two experiments were that experiment 2 removed several variables, such as the participants' waving direction, the presence of the music effect and the age group, from the original paradigm of experiment 1 and introduced one new variable (participants' beliefs) to that paradigm. Furthermore, two additional types of visual stimuli (a mechanical pendulum and a moving dot) were adopted to compare the participants' reactions to different types of visual stimuli.

Experiment 3

In the final experiment, participants were required to interact with KASPAR2 using a few gesture patterns. During this process, the humanoid robot tried to coordinate its movement speed to match the participants' movement speed when they were both performing the same gesture pattern simultaneously. This experiment was proposed to test whether a humanoid robot with behaviour adaptation (the meaning of 'adaptation' in this experiment was specified to movement speed adaptation, which could also be regarded as motor coordination) capability could improve humans' perception to this robot in human-humanoid interaction. The behaviour adaptation mechanism implemented on KASPAR2 in the experiment was based on the information distance synchrony detection method. This experiment also examined the effectiveness of this method in real-time human-humanoid interaction.

6.2 Review of the Research Questions

In this section, the research questions proposed in Chapter 1 are reviewed one after another.

1. Can a method be developed that can be used in real time to detect synchrony in Human-Humanoid Interaction?

In Chapter 3, the development and primary validation process of the information distance synchrony detection method was depicted. Experiment 3 (the experiment reported in Chapter 5) demonstrated that this information distance synchrony detection method could be applied to detect the movement synchrony between a human and a humanoid robot in real-time human-humanoid interaction.

2. A) Can an interference effect be found in a playful Human-Robot Interaction experiment using a social robot that does not behave according to a biological motion profile?
   B) Can a human's motor coordination be elicited using the same social robot and the same experimental setup as in 2. A)?

For research question 2 A), the experimental results of experiment 1 (the first experiment reported in Chapter 4) suggested that the interference effect was only found when the participants were waving vertically with the music turned on. A possible explanation could be that the influence to the movement variance amount between music-on and music-off conditions had a greater impact to the vertical waving condition than to the horizontal waving condition and might consequently facilitate the interference effect. Moreover, the results of experiment 2 (the second experiment reported in Chapter 4) can also be used to answer question 2 A), which found the interference effect tended to be significant when the participants were interacting with KASPAR2.

For research question 2 B), it was found in over 81% of the experimental trials of experiment 1 that the movement rhythm of the participants' actions were synchronized with the rhythm of the humanoid robot's actions. This result implied that the participants tended to coordinate their movement rhythm to KASPAR2's movement rhythm.

3. A) Can a human's belief have an impact on producing an interference effect when interacting with the same robot mentioned in question 2?
   B) Can a social robot elicit a human's motor coordination compared with a virtual moving dot or a mechanical pendulum?

The results of experiment 2 suggested that the interference effect tended to be significant for the engaged instruction group (participants in this group believed that KASPAR2 was engaged in the interaction) but appeared to be insignificant for the not-engaged instruction group (participants in this group believed that KASPAR2 was not engaged in the interaction). This part of the results suggested that the belief of the participants about the engagement of the humanoid robot had at least an important impact, if not critical, on eliciting the interference effect in experiment 2.

For research question 2 B), the results of motor coordination analysis of experiment 2 indicated that the preference of the participants to coordinate their movements to KASPAR2's movement rhythm was significantly higher than that to the mechanical pendulum, but not significantly higher than that to the moving dot. It was not surprising that there was no significant difference in movement synchronization between experiments with the humanoid robot and the moving dot as the moving dot was an abstract and ambiguous object. Unlike an embodied mechanical pendulum, which did not leave much room for imagination, the source of the trajectories of the moving dot was open for the participants to interpret. Therefore, it was possible that the moving dot could induce a similar effect as the humanoid robot did in movement synchronization. According to the average information distance values, the humanoid robot was still the most favoured visual stimulus of the participants.

4. A) Can the synchrony detection method be developed and used in real-time to help a social robot to adapt its behaviour to a human's behaviour?

   B) Will a human prefer a social robot that adapts to his/ her behaviour compared to a social robot that does not adapt to his/her behaviour?

The answer for question 4 A) is similar to the answer for question 1. In experiment 3, the information distance synchrony detection method was employed as the core part of the behaviour adaptation mechanism realized on KASPAR2. It successfully helped KASPAR2 to adapt its movement speed to the participants' movement speed in real-time interaction.

According to the questionnaire feedback from the participants, 66.7% of the participants preferred to interact with KASPAR2 in the adaptation condition; 16.7% of the participants preferred to interact with KASPAR2 in the non-adaptation condition; the rest of the participants had no preference or could not tell the difference between the adaptation condition and the baseline condition. The result of the Chi-square test also suggested that the adaptation interaction with the robot was the most commonly preferred by the participants. Therefore, these results indicated that the majority of the participants preferred a social robot that adapted to their behaviour. However, it is worth noticing that the ratings for the adaptation interaction were not significantly higher than the ratings for the baseline condition for Q3 and Q4. A possible explanation for this discrepancy was that the participants might be misled in the interaction and regarded inspecting the gesture recognition capability of the robot as the core objective of the experiment and therefore got confused with the purpose of these questions. Another possible explanation was that the participants might not fully understand the meaning of a few terms, such as 'social interaction', in the context of Human-Robot Interaction. This situation might also reflect a limitation of the application of questionnaires: the participants who answered the questionnaires might not understand the questions as well as the designers did. In addition, it is not rare in HRI studies that the questionnaire results on the participants' experience are not very informative or might even contradict the results of the participants' behaviour in the experiments (Kose-Bagci et al. 2010). It has been suggested that the participants' ratings to the questionnaires and their actual behaviours in the experiments should be used together to describe the participants' response to the robots (Kiesler and Goetz 2002). Hence, the importance of using supplementary criteria or measures such as motor interference and information distance to characterize the participants' behaviours in their interaction with the robots.

6.3 Summary of Contributions to Knowledge

The main contributions of this thesis are summarized as follows:

1. Introduced a novel method to measure synchrony between two agents' behaviours using information distance and validated the performance of this method in real-time human-humanoid interaction.

2. Performed a set of experiments to investigate motor interference phenomenon and found that human observers' overall perception of a robot as a 'social entity' (in this thesis, the term 'overall perception' refers to the human observer's overall perceptions of a robot in terms of appearance, motion, observers' beliefs and environmental features as related to a 'social entity') instead of any individual appearance or motion feature might possibly be the factor that is critical to elicit the interference effect in human-humanoid interaction.

3. Performed a set of experiments to investigate motor coordination between humans and different types of visual stimuli and found that the participants preferred to coordinate their movements to the agent with the best 'overall perception' as a social entity.

4. Proposed a new experimental paradigm, in which a humanoid robot could coordinate its movements to a human with the information distance method as the synchrony measure.

5. Performed an experiment using the proposed experimental paradigm concerning motor coordination in human-humanoid interaction. The experimental results validated the design of the paradigm. Furthermore, the survey feedback from the participants indicated that a humanoid robot with motor coordination capability could enhance its social competence and improve the perception of the participants to this humanoid robot.

Chapter 7
Conclusion and Future Directions

7.1 Conclusion

The central thesis of this dissertation is to present studies from two perspectives to investigate possible means of improving the social competence of a humanoid robot in order to induce natural interaction between the humanoid robot and a human. One perspective concentrates more on realizing the actual functionality of a humanoid robot. A valid approach to enhance the social competence of a humanoid robot by enabling the humanoid robot to adapt its behaviour to a human's behaviour is demonstrated. The development process of a novel method to measure behaviour synchrony using information distance is also depicted, which is employed as the fundamental basis to support the behaviour adaptation mechanism. Meanwhile, the other perspective is more observer-dependent. Motor interference, which reflects a human's subconscious perception of an agent, is used as a potential metric to measure the social competence of a humanoid robot. It provides a possible mean to investigate the influence of different features on humans' perception of the robot, which may establish a potential guideline of designing humanoid robots with adequate levels of social competence.

The studies presented in this dissertation are motivated by research in human social interactions concerning the motor resonance framework and the behaviours related to this framework, motor interference, motor coordination and immediate imitation. The special criteria required for the presence and absence of motor interference and the facilitation of social rapport or liking of motor coordination largely inspire the investigation as well as the application of the similar effect or mechanism in social interaction between a human and a robot.

For the experiments carried out to investigate the behaviour adaptation mechanism, the process of these experiments showed that the information distance synchrony detection method was capable of functioning in real-time in human-humanoid interaction. The experimental results indicated that a humanoid robot with the support of this synchrony detection method could successfully adapt its behaviour to match the behaviour of a human. The questionnaire feedback from the participants implied that the behaviour adaptation mechanism had a positive effect on the social competence of the humanoid robot.

For the experiments performed to investigate motor interference and motor coordination simultaneously, it was found that a humanoid robot without biological motion profile could elicit the interference effect in human observers' behaviours. The experimental results also suggested that both the participants' beliefs and the application of music might facilitate the elicitation of the interference effects. Based on these findings, it was further hypothesized that the application of individual features, such as the observers' beliefs, music, biological motion and human-like appearance, may all potentially contribute to the overall perception of a humanoid robot as a 'social entity'. This overall perception of a humanoid robot, instead of any individual features, is critical to elicit the interference effect in human-humanoid interaction. In the investigation of motor coordination, it was found that humans tended to synchronize their movement rhythm to the movement rhythm of a humanoid robot even they were not instructed to do so.

7.2 Future Directions

A number of possible directions for future research are under consideration. The first direction is to complement the present studies of motor interference by introducing baseline or neutral conditions. In this thesis, no baseline or neutral condition was introduced to the two experiments concerning motor interference investigation. The main reason was to reduce the duration of the experiments to ensure the participants could maintain a relatively high level of concentration through out the entire experiments. In the previous research on motor interference, the usage of baseline or neutral condition were present in many studies (Bouquet et al. 2007, Kilner et al. 2007) and also absent in many others (Chaminade et al. 2005, Stanley et al. 2007). It is possible that introducing baseline or neutral conditions in the future experiments as supplements may make the outcome of the experiments more comprehensive and more comparable to other studies that involved baseline or neutral conditions as well. In addition, the effect of music can also be further investigated through this modification of the experimental paradigm, as proposed in Chapter 4.

The second possible direction is to design new experiments to examine the hypothesis that the overall perception of a humanoid robot is critical to elicit the interference effect in human-humanoid interaction. As there are many factors that can influence the overall perception of a humanoid robot, it may require far more than one single experiment to test the validity of this hypothesis. In the experiment reported by Stanley et al. (Stanley et al. 2007), human participants' beliefs exhibited greater impact on eliciting the interference effect than the biological motion profile when the participants were observing the movements performed by a virtual moving dot. In the experiment described in this thesis, the biological motion profile was not introduced as a part of the humanoid robot's behaviour.

Consequently, its influence to the overall perception of a humanoid robot was not investigated in the present studies. Therefore, whether the effect depicted in Stanley et al.'s work can be replicated when humans are observing the movements performed by a humanoid robot is a potential next step of future research.

The final direction is to further extend the present behaviour adaptation mechanism to enable a humanoid robot to realize more complex social behaviours such as bi-directional motor coordination as suggested by Marin et al.'s study (Marin et al. 2009). In the experiments present in this thesis, single direction motor coordination, i.e. a human coordinates his / her behaviour to a humanoid robot and a humanoid robot coordinates its behaviour to a human, were both realized in different experiments. The next step is to combine the two types of single direction motor coordination in one experimental scenario. Mechanisms need to be developed to enable a humanoid robot to be aware of the coordination behaviour of a human in their interaction and make appropriate response to that behaviour.

Appendix A
Publications

The work reported in this thesis has contributed to three publications, including one international peer-reviewed conference paper and one journal article. The first author of these articles conducted all the research and wrote the first complete draft of the articles. The co-authors provided feedback on this draft. These publications are listed as follows with brief description of the relationship between these publications and the thesis:

1. Qiming Shen, Joe Saunders, Hatice Kose-Bagci, Kerstin Dautenhahn, (2008), “Acting and Interacting Like Me? A Method for Identifying Similarity and Synchronous Behaviour between a Human and a Robot,” *Poster Presentation at IEEE IROS Workshop on "From motor to interaction learning in robots"*, 26, September, 2008, Nice, France. This paper initially reports the information distance synchrony detection method presented in Chapter 3.

2. Qiming Shen, Hatice Kose-Bagci, Joe Saunders, Kerstin Dautenhahn, (2009), "An Experimental Investigation of Interference Effects in Human-Humanoid Interaction Games," *the 18th IEEE International Symposium on Robot and Human Interactive Communication*: 291-298. This paper describes the first experiment reported in Chapter 4, which investigated the impact of music, age group and waving

direction on motor interference and motor coordination. Note, since the publication of this article the data has been reanalysed and an error in the data analysis was corrected. Due to this error the results reported in the article differ from the (correct) results reported in Chapter 4.

3. Qiming Shen, Hatice Kose-Bagci, Joe Saunders, Kerstin Dautenhahn, (2011), "The Impact of Participants' Beliefs on Motor Interference and Motor Coordination in Human–Humanoid Interactions," *IEEE Transactions on Autonomous Mental Development* 3(1): 6-16. This paper describes the second experiment reported in Chapter 4, which investigated the impact of various types of visual stimuli and participants' beliefs on motor interference and motor coordination.

Appendix B
Source Code CD

In the studies reported in this thesis, a significant amount of software development effort was required. The main source code that has been developed is listed as follows:

1. im_imitation.cpp, this program was developed to realize the immediate imitation function on KASPAR2. It was developed based on ARToolkit.

2. info_dist.cpp, this program was developed to realize the information distance synchrony detection method.

3. waveH.cpp, this program was developed to enable KASPAR2 to wave horizontally in experiment 1 and 2.

4. waveV.cpp, this program was developed to enable KASPAR2 to wave vertically in experiment 1 and 2.

5. MovingDot.java, this program was developed to generate a virtual moving dot, which was used in experiment 2.

6. exp3_pra.cpp, this program was developed for the practice trial in experiment 3.

7. exp3_non.cpp, this program was developed for the non-adaptation condition of the formal interaction trial in experiment 3. It has the information distance method embedded to detect the movement synchrony between the participants and KASPAR2.

8. exp3_ada.cpp, this program was developed for the adaptation condition of the formal interaction trial in experiment 3. It also has the information distance method embedded to detect the movement synchrony between the participants and KASPAR2.

Bibliography

Acapela-group.com (2010). "Acapela Text to Speech Demo," Retrieved 5 June, 2010, from http://www.acapela-group.com/text-to-speech-interactive-demo.html.

Adams, B., Breazeal, C., Brooks, R.A., Scassellati, B. (2000). "Humanoid robots: a new kind of tool," *IEEE Intelligent Systems* 15(4): 25–31.

Adams, J. A., Skubic, M. (2005). "Introduction to the Special Issue on Human-Robot Interaction," *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans* 35(4): 433 - 437.

Agam, G. (2006). "Introduction to programming with OpenCV," Retrieved 7, May, 2011, from http://www.cs.cornell.edu/courses/cs4670/2010fa/projects/Introduction%20to%20Programming%20With%20OpenCV.pdf.

Alicke, M., Smith, R., Klotz, M. (1986). "Judgements of physical attractiveness: the role of faces and bodies," *Personality and Social Psychology Bulletin* 12(4): 381–389.

Asfour, T., Berns, K., Dillmann, R. (1999). "The humanoid robot ARMAR," *Proceedings of the Second International Symposium on Humanoid Robots*: 174–180.

Atkeson, C. G., et al. (2000). “Using humanoid robots to study human behaviour,” *IEEE Intelligent Systems* 15: 46–56.

Bakari, M. J., Seward, D. W., Shaban, E. M., Agate, R. Y. (2006). “Multi-Arm Mobile Robot for Hazardous Nuclear Decommissioning Tasks,” *Proceedings of the 23rd International Symposium on Automation and Robotics in Construction*: 231 – 236.

Bartneck, C., Kulic, D., Croft, E., Zoghbi, S. (2009). “Measurement instruments for the anthropomorphism, animacy, likability, perceived safety of robots,” *International Journal of Social Robotics* 1: 71–81.

Bernieri, F. J., Rosenthal, R. (1991). “Interpersonal coordination: Behavior matching and interactional synchrony,” *Fundamentals of nonverbal behavior. Studies in emotion & social interaction*. R. S. Feldman, B. Rime (Eds.), New York, Cambridge University Press: 401- 432.

Bischoff, R. (1999). “Advances in the Development of the Humanoid Service Robot HERMES,” *Second International Conference on Field and Service Robotics (FSR’99)*, Pittsburgh, PA.

Blakemore, S. J., Frith, C. (2005). “The role of motor contagion in the prediction of action,” *Neuropsychologia* 43: 260–267.

Blow, M., Dautenhahn, K., Appleby, A., Nehaniv, C. L., Lee, D. (2006). “The Art of Designing Robot Faces - Dimensions for Human-Robot Interaction,” *Proc. AMC International Conference on Human-Robot Interaction (HRI06)*. Salt Lake City, Utah, USA: 331 - 332.

Bouquet, C. A., Gaurier, V., Shipley, T., Toussaint, L., Blandin, Y. (2007). "Influence of the perception of biological or non-biological motion on movement execution," *Journal of Sports Sciences* 25: 519-530.

Brass, M., Bekkering, H., Wohlschlager, A., Prinz, W. (2000). "Compatibility between observed and executed finger movements: comparing symbolic, spatial, and imitative cues," *Brain and Cognition* 44(2): 124–143.

Breazeal, C., Scassellati, B. (1999). "A context-dependent attention system for a social robot," *Proceedings of the International Joint Conference on Artificial Intelligence*. Stockholm, Sweden: 1146–1153.

Breazeal, C. (2003). "Toward sociable robots," *Robotics and Autonomous Systems* 42: 167–175.

Buccino, G., Binkofski, F., Fink, G. R., Fadiga, L., Fogassi, L., Gallese, V., et al. (2001). "Action observation activates premotor and parietal areas in a somatotopic manner: an fMRI study," *European Journal of Neuroscience* 13(2): 400–404.

Buekers, M. J., Bogaerts, H. P., Swinnen, S. P., Helsen, W. F. (2000). "The synchronization of human arm movements to external events," *Neuroscience Letters* 290: 181–184.

Casper, J. (2002). "Human-Robot Interactions During the Robot-Assisted Urban Search and Rescue Response at the World Trade Center," M. S. thesis, Tampa, Univer. South Florida.

Casper, J., Murphy, R. (2003). “Human-robot interaction during the robot-assisted urban search and rescue effort at the world trade center,” *IEEE Transactions on Systems, Man and Cybernetics, Part B: Cybernetics* 33(3): 367 - 385

Castaneda, K., (2006). “Nintendo and PixArt Team Up.” Retrieved 3 May, 2012, from http://www.nintendoworldreport.com/news/11557.

Chaminade, T., Franklin, D. W., Oztop, E. Cheng, G. (2005). “Motor interference between Humans and Humanoid Robots: Effect of Biological and Artificial Motion,” *Proceedings of the 4th International Conference on Development and Learning*: 96-101.

Chaminade, T., Hodgins, J. K. (2006). “Artificial agents in social cognitive sciences,” *Interaction Studies* 7(3): 347–353.

Chartrand, T. L., Bargh, J. A. (1999). “The chameleon effect: the perception-behavior link and social interaction,” *Journal of Personality and Social Psychology* 76(6): 893–910.

Cheng, G., Nagakubo, A., Kuniyoshi, Y. (2001). “Continuous humanoid interaction: An integrated perspective — gaining adaptivity, redundancy, flexibility — in one, Robot,” *Robotics and Autonomous Systems* 37: 161–183.

Cover, T. M., Thomas, J. A. (1991). *Elements of Information Theory*, John Wiley & Sons, Inc.

Crutchfield, J. P. (1990). “Information and its Metric,” *Nonlinear Structures in Physical Systems – Pattern Formation, Chaos and Waves*. L. Lam, H. Morris (Eds.). New York, Springer Verlag: 119-130.

Dautenhahn, K. (1995). “Getting to know each other – artificial social intelligence for autonomous robots,” *Robotics and Autonomous Systems* 16: 333–356.

Dautenhahn, K. (1998). “The art of designing socially intelligent agents—science, fiction, and the human in the loop,” *Applied Artificial Intelligence Journal* 12(7–8): 573–617.

Dautenhahn, K., Billard, A. (1999). “Bringing up Robots or - The Psychology of Socially Intelligent Robots: From Theory to Implementation,” *Proc. Autonomous Agents (Agents '99)*. Seattle, Washington, USA: 366-367.

Dautenhahn, K. (1999). “Embodiment and Interaction in Socially Intelligent Life-Like Agents,” *Computation for Metaphors, Analogy and Agent, Springer Lecture Notes in Artificial Intelligence*, C. L. Nehaniv (Eds.), Springer. 1562: 102-142.

Dautenhahn, K., Walters, M., Woods, S., Koay, K. L., Nehaniv, C. L., Sisbot, A., Alami, R., Siméon, T. (2006). “How may I serve you?: a robot companion approaching a seated person in a helping context,” *HRI '06 Proceedings of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction*. New York, NY, USA: 172 - 179.

Dautenhahn, K. (2007). "Methodology and themes of human-robot interaction: a growing research field," *International Journal of Advanced Robotic Systems* 4(1): 103-108.

Dehais, F., Sisbot, E. A., Alami, R., Causse, M. (2011). "Physiological and subjective evaluation of a human-robot object hand-over task," *Applied Ergonomics* 2(6): 785–791.

DiSalvo, C., Gemperle, F., Forlizzi, J., Kiesler, S. (2002). "All robots are not created equal: The design and perception of humanoid robot heads," *Proceedings of the Conference on Designing Interactive Systems*.

Duffy, B., Joue, G., Bourke, J. (2002). "Issues in assessing performance of social robots," *Proceedings of the Second WSEAS International Conference*, RODLICS, Greece.

Duffy, B. R. (2003). "Anthropomorphism and the social robot," *Robotics and Autonomous Systems* 42: 177-190.

Fong, T., Nourbakhsh, I., Dautenhahn, K. (2002). "A survey of socially interactive robots: concepts, design, and applications," Technical Report No. CMU-RI-TR-02-29, Robotics Institute, Carnegie Mellon University.

Fong, T., Nourbakhsh, I., Dautenhahn, K. (2003). "A survey of socially interactive robots," *Robotics and Autonomous Systems* 42: 143–166.

Gallese, V., Fadiga, L., Fogassi, L., Rizzolatti G. (1996). "Action recognition in the premotor cortex," *Brain* 119: 593-609.

Goetz, J., Kiesler, S., Powers, A. (2003). “Matching robot appearance and behavior to tasks to improve human-robot cooperation,” *Proceedings of the 12th IEEE international workshop on robot and human interactive communication*, Berkeley, CA, USA: 55-60.

Gong, L., Nass, C. (2007). “When a talking-face computer agent is half-human and half-humanoid: human identity and consistency preference,” *Journal of Human Communication Research* 33(2): 163–193.

Goodrich, M. A., Schultz, A. C. (2007). “Human-Robot Interaction: A Survey,” *Human-Computer Interaction* 1(3): 203-275.

Green, S. A., Billinghurst, M., Chen, X., Chase, G. J. (2008). “Human-Robot Collaboration: A Literature Review and Augmented Reality Approach in Design,” *International Journal of Advanced Robotic Systems* 5(1): 1-18.

Hale, J. G., Pollick, F.E. (2005). “‘Sticky Hands’: learning and generalization for cooperative physical interactions with a humanoid robot,” *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews* 35(4): 512 - 521.

Hari, R., Forss, N., Avikainen, S., Kirveskari, E., Salenius, S., Rizzolatti, G. (1998). “Activation of human primary motor cortex during action observation: A neuromagnetic study,” *Proc. Nat. Acad. Sci. USA*. 95: 15061-15065.

Heyes, C. (2011). “Automatic imitation,” *Psychological bulletin* 137(3): 463–483.

Hinds, P. J., Roberts, T. L., Jones, H. (2004). “Whose job is it anyway? A study of human-robot interaction in a collaborative task,” *Human-Computer Interaction* 19: 151-181.

Hirai, K., Hirose, M., Haikawa, Y., Takenaka, T. (1998). “The development of Honda humanoid robot,” *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*. Leuven, Belgium: 1321–1326.

Hubbard, A. S. E. (2000). “Interpersonal coordination in interactions: Evaluations and social skills,” *Communication Research Reports* 17: 95-104.

Huber, M., Rickert, M., Knoll, A., Brandt, T., Glasauer, S. (2008). “Human-Robot Interaction in Handing-Over Tasks,” *The 17th IEEE International Symposium on Robot and Human Interactive Communication, RO-MAN 2008*. Universität München, Munich, Germany: 107 - 112.

Hüttenrauch, H., Green, A., Norman, M., Oestreicher, L., Eklundh, K. S. (2004). “Involving Users in the Design of a Mobile Office Robot,” *IEEE Transactions on Systems, Man and Cybernetics, Part C: Applications and Reviews* 34(2): 113 - 124.

Inamura, T., Okada, K., Tokutsu, S., Hatao, N., Inaba, M., Inoue, H., (2009). “HRP-2W: A humanoid platform for research on support behavior in daily life environments,” *Robotics and Autonomous Systems* 57(2): 145–154.

Jones, H., Rock, S., Burns, D., Morris, S. (2002). “Autonomous robots in swat applications: Research, design, and operations challenges,” *Proc. 2002 Symp. Association Unmanned Vehicle Systems Int.*

Kaplan, F., Hafner, V. (2005). “Mapping the space of skills: An approach for comparing embodied sensorimotor organizations,” *Proc. 4th IEEE International Conference on Development and Learning (ICDL-05)*: 129–134.

Kato, H., Billinghurst, M. (1999). “Marker Tracking and HMD Calibration for a video-based Augmented Reality Conferencing System,” *Proceedings of the 2nd International Workshop on Augmented Reality (IWAR 99)*, San Francisco, USA.

Keysers, C., Kohler, E., Umiltà, M. A., Nanetti, L., Fogassi, L., Gallese, V. (2003). “Audiovisual mirror neurons and action recognition,” *Experimental Brain Research* 153(4): 628-636.

Kiesler, S., Goetz, J. (2002). "Mental models of robotic assistants," *Proceedings of the CHI '02 extended abstracts on Human factors in computing systems*, Minneapolis, Minnesota, USA.

Kilner, J., Hamilton, A. F. de C., Blakemore, S.-J. (2007). “Interference effect of observed human movement on action is due to velocity profile of biological motion,” *Social Neuroscience* 2(3-4): 158-166.

Kilner, J. M., Paulignan, Y., Blakemore, S. J. (2003). “An interference effect of observed biological movement on action,” *Current Biology* 13(6): 522-525.

Klyubin, A. S., Polani, D., Nehaniv, C. L. (2004). "Organization of the Information Flow in the Perception-Action Loop of Evolved Agents," *Proceedings of 2004 NASA/DoD Conference on Evolvable Hardware*, IEEE Computer Society.

Kose-Bagci, H., Dautenhahn, K., Syrdal, D. S., Nehaniv, C. L. (2010), "Drum-mate: Interaction dynamics and gestures in human-humanoid drumming experiments," *Connection Science* 22(2): 103 – 134.

Kupferberg, A., Glasauer, S., Huber, M., Rickert, M., Knoll, A., Brandt, T. (2009). "Video observation of humanoid robot movements elicits motor interference," *Proceedings New Frontiers in Human-Robot Interaction*, K. Dautenhahn (Eds.), *symposium at the AISB09 convention*. Edinburgh, Scotland: 81-85.

Kupferberg, A., Glasauer, S., Huber, M., Rickert, M., Knoll, A., Brandt, T. (2011). "Biological movement increases acceptance of humanoid robots as human partners in motor interaction," *AI & Society* 26(4): 339–345.

LaFrance, M. (1979). "Nonverbal synchrony and rapport: Analysis by the cross-lag panel technique," *Social Psychology Quarterly* 42: 66–70.

Lakin, J. L., Chartrand, T. L. (2003). "Using nonconscious behavioral mimicry to create affiliation and rapport," *Psychological Science* 14: 334–339.

Likert, R. (1932). "A technique for the measurement of attitudes," *Archives of Psychology*, 140.

Loughborough University (2013). “Questionnaire Design,” Retrieved 28 Feb, 2013, from http://www.lboro.ac.uk/media/wwwlboroacuk/content/library/downloads/advicesheets/questionnaire.pdf.

Marin, L., Issartel, J., Chaminade, T. (2009). “Interpersonal motor coordination: from human-human to human-robot interactions,” *Interaction Studies* 10(3): 479-504.

Minato, T., Shimada, M., Ishiguro, H., Itakura, S. (2004). “Development of an android robot for studying human–robot interaction,” *Innovations in Applied Artificial Intelligence* B. Orchard, C. Yang, M. Ali (Eds.). Berlin, Springer: 424–434.

Mirza, N. (2008). Grounded Sensorimotor Interaction Histories for Ontogenetic Development in Robots, PhD thesis, University of Hertfordshire.

Mirza, N. A., Nehaniv, C. L., Dautenhahn, K., te Boekhorst, R. (2005a). “Using sensory-motor phase-plots to characterise robot-environment interactions,” *Proceedings 2005 IEEE International Symposium on Computational Intelligence in Robotics and Automation (CIRA 2005)*. Espoo, Finland: 581–586.

Mirza, N. A., Nehaniv, C. L., Dautenhahn, K., te Boekhorst, R. (2005b). “Using temporal information distance to locate sensorimotor experience in a metric space,” *Proc. 2005 IEEE Congress on Evolutionary Computation.* Edinburgh, Scotland, IEEE Press. 1: 150–157.

Mirza, N. A., Nehaniv, C. L., Dautenhahn, K., te Boekhorst, R. (2006). "Interaction histories: From experience to action and back again," *Proceedings of the 5th IEEE International Conference on Development and Learning (ICDL 2006)*, Bloomington, IN, USA.

Mori, M. (1970). "The Uncanny Valley," *Energy* 7(4): 33-35.

Murphy, R. R. (2004). "Human–Robot Interaction in Rescue Robotics," *IEEE Transactions on Systems, Man and Cybernetics, Part C: Applications and Reviews* 34(2): 138 - 153

Nadel, J., Guerini, C., Peze, A., Rivet, C. (1999). "The evolving nature of imitation as a format of communication," *Imitation in Infancy*, J. Nadel, G. Butterworth (Eds.). Cambridge: 209–234.

Nakauchi, Y., Simmons, R. (2000). "A social robot that stands in line," *Proceedings of the International Conference on Intelligent Robots and Systems*.

Nehaniv, C. L., Dautenhahn, K. (2002). "The Correspondence Problem," *Imitation in Animals and Artifacts*. K. Dautenhahn, C. L. Nehaniv (Eds.), MIT Press: 41–61.

Nintendo.co.uk (2010). "Nintendo UK's official site," Retrieved 3 May, 2012, from http://www.nintendo.co.uk/NOE/en_GB/index.html.

Nintendo-europe.com (2011). "Thank you for selecting the Wii console," Retrieved 3 May, 2012, from http://www.nintendo.co.uk/NOE/images /service/Wii_HW_SystemSetup_MAN_RVK_UK_NFRP_2011.pdf.

Olsson, L., Nehaniv, C. L., Polani, D. (2005). “Sensor adaptation and development in robots by entropy maximization of sensory data,” *Proceedings of the Sixth IEEE International Symposium on Computational Intelligence in Robotics and Automation (CIRA-2005)*, IEEE Computer Society Press: 587-592.

Olsson, L., Nehaniv, C. L., Polani, D. (2006a). “From unknown sensors and actuators to actions grounded in sensorimotor perceptions,” *Connection Science* 18(2): 121–144.

Olsson, L., Nehaniv, C. L., Polani, D. (2006b). “Measuring informational distances between sensors and sensor integration,” *Artificial Life X*, MIT Press.

Olsson, L. A. (2006). Information Self-structuring for Developmental Robotics: Organization, Adaptation and Integration. PhD thesis, University of Hertfordshire.

Onakasuita.org (2010). “WiinRemote,” Retrieved 4 May, 2012, from http://onakasuita.org/wii/index-e.html.

Oxford Dictionaries, (2011). “Definition of rhythm - rhythm, music and faculty,” Retrieved 5 December, 2011, from http://oxforddictionaries.com/definition/english/rhythm?view=uk.

Oztop, E., Franklin, D. W., Chaminade, T., Cheng, G. (2005). “Human-humanoid interaction: is a humanoid robot perceived as a human?” *International Journal of Humanoid Robotics* 2(4): 537-559.

Press, C., Bird, G., Flach, R., Heyes, C. (2005). "Robotic movement elicits automatic imitation," *Brain Research: Cognitive Brain Research* 25(3): 632-640.

Press, C., Gillmeister, H., Heyes, C. (2006). "Bottom-up, not top-down, modulation of imitation by human and robotic models," *European Journal of Neuroscience* 24(8): 2415-2419.

Rajko, S., Qian, G., Ingalls, T. (2008). "AME Patterns library - a generic, open source C++ library for pattern recognition," Retrieved 7 June, 2010, from http://mast.mat.ucsb.edu/docs/paper_43.pdf.

Rani, P., Sims, J., Brackin, R., Sarkar, N. (2002). "Online stress detection using psychophysiological signal for implicit human-robot cooperation," *Robotica* 20(6): 673–686.

Repp, B. H., Penel, A. (2004). "Rhythmic movement is attracted more strongly to auditory than to visual rhythms," *Psychological Research* 68: 252–270.

Restivo, S. (2001). "Bringing up and booting up: Social theory and the emergence of socially intelligent robots," *Proceedings of the IEEE Conference on SMC*.

Richardson, M. J., Marsh, K. L., Schmidt, R. C. (2005). "Effects of visual and verbal interaction on unintentional interpersonal coordination," *Journal of Experimental Psychology: Human Perception and Performance* 31(1): 62-79.

Rizzolatti, G., Fadiga, L., Gallese, V., Fogassi, L. (1996). “Premotor cortex and the recognition of motor actions,” *Cognitive Brain Research* 3: 131-141.

Robins, B., Dautenhahn, K., te Boekhorst, R., Billard, A. (2004). “Effects of repeated exposure to a humanoid robot on children with autism,” *Designing a More Inclusive World*, S. Keates, J. Clarkson, P. Langdon, P. Robinson, (Eds.). London, Springer Verlag: 225-236.

Robins, B., Dautenhahn, K., te Boerkhorst, R., Billard, A. (2004a). “Robots as assistive technology - does appearance matter?” *Proc. IEEE RO-MAN 2004, 13th IEEE International Workshop on Robot and Human Interactive Communication*, Kurashiki, Okayama Japan, IEEE Press: 277- 282.

Robins, B., Dautenhahn, K., Nehaniv, C. L., Mirza, N. A., Francois, D., Olsson, L. (2005). “Sustaining interaction dynamics and engagement in dyadic child-robot interaction kinesics: Lessons learnt from an exploratory study,” *Proc. 14th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN 2005).* Nashville, USA, IEEE Press: 716-722.

Robins, B., Dautenhahn, K., te Boekhorst, R., Nehaniv, C. L. (2008). “Behaviour Delay and Robot Expressiveness in Child-Robot Interactions: A User Study on Interaction Kinesics,” *Proc. ACM/IEEE 3rd International Conference on Human-Robot Interaction (HRI 2008).*

Sabanovic, S., Michalowski, M. P., Caporael, L. R. (2007). "Making friends: building social robots through interdisciplinary collaboration," *Multidisciplinary collaboration for socially assistive robotics: papers from the AAAI spring symposium* (Technical Report SS-07-07): 71–77.

Scassellati, B. (2000). "Investigating models of social development using a humanoid robot," *Biorobotics*. B. Webb, T. Consi (Eds.). Cambridge, MA, MIT Press.

Schmidt, R. C., Richardson, M. J., Arsenault, C., Galantucci, B. (2007). "Visual Tracking and Entrainment to an Environmental Rhythm," *Journal of Experimental Psychology: Human Perception and Performance* 33(4): 860–870.

Schmidt, R. C., Richardson, M.J. (2008). "Dynamics of interpersonal coordination," *Coordination: Neural, Behavioural and Social Dynamics*. A. Fuchs, V. Jirsa, (Eds.). Heidelberg, Springer-Verlag: 281-307.

Scholtz, J., Theofanos, M., Antonishek, B. (2006). "Development of a Test Bed for Evaluating Human-Robot Performance for Explosive Ordnance Disposal Robots," *Proceedings of Human Robot Interaction 2006*. Salt Lake City, UT: 10-17.

Sciencedaily.com (2008). "Nintendo Wii With A New Mission: Wiimote As An Interface Bridging Mind And Body," Retrieved 4 May, 2012, from http://www.sciencedaily.com/releases/2008/03/080304200905.htm.

Sciutti, A., Bisio, A., Nori, F., Metta, G., Fadiga, L., Pozzo, T., Sandini, G. (2012). “Measuring Human-Robot Interaction Through Motor Resonance,” *International Journal of Social Robotics* 4: 223–234.

Severinson-Eklund, K., Green, A., Hüttenrauch, H. (2003). “Social and collaborative aspects of interaction with a service robot,” *Robotics and Autonomous Systems* 42: 223–234.

Shannon, C. E. (1948). “A mathematical theory of communication,” *Bell Systems Technical Journal* 27: 379-423 and 623-656.

Stanley, J., Gowen, E., Miall, R.C. (2007). “Interference in performed movement during observation of a moving dot stimulus,” *Journal of Experimental Psychology: Human Perception and Performance* 33: 915-926.

Syrdal, D. S., Koay, K.-L., Walters, M. L., Dautenhahn, K. (2007a). “A personalised robot companion? The role of individual differences on spatial preferences in HRI scenarios,” *IEEE international symposium on robot and human interactive communication (RO-MAN07)* Jeju Island, Korea: 26–29.

Syrdal, D. S., Dautenhahn, K., Woods, S., Walters, M., Koay, K. L. (2007b). “Looking good? Appearance preferences and robot personality inferences at zero acquaintance,” *Multidisciplinary collaboration for socially assistive robotics: papers from the AAAI spring symposium*. (Technical Report SS-07-07: 86-92).

The MathWorks, Inc. (2008). “MATLAB – The Language of Technical Computing,” Retrieved 15 Feburary, 2008, from http://www. mathworks.com/ products/matlab/.

Tomasello, M. (1998). “Uniquely primate, uniquely human.” *Developmental Science* 1: 1–30.

University of Hertfordshire, (2007). “KASPAR, Kinesics and Synchronisation in Personal Assistant Robotics,” Retrieved 24 October, 2007, from http://kaspar.feis.herts.ac.uk.

Van Ulzen, N. R., Lamoth, C. J., Daffertshofer, A., Semin, G. R., Beek, P. J. (2008). “Characteristics of instructed and uninstructed interpersonal coordination while walking side-by-side,” *Neuroscience Letters* 432: 88-93.

Volpe, R. (1997). “Rocky 7: A next generation mars rover prototype,” *Journal of Advanced Robotics* 11(4): 341–358.

Wada, K., Shibata, T., Saito, T., Tanie, K. (2004). “Effects of Robot Assisted Activity for Elderly People and Nurses at a Day Service Center, Special Issue on Human Interactive Robots,” *Special Issue on Human Interactive Robots for Psychological Enrichment, Proceedings of the IEEE* 92(11): 1780 - 1788.

Wada, K., Shibata, T., Musha, T., Kimura, S. (2005). “Effects of robot therapy for demented patients evaluated by EEG,” *Proc IEEE/RSJ int. conf. intelligent robots and systems (IROS)*: 1552–1557.

Walters, M. L., Syrdal, D. S., Dautenhahn, K., te Boekhorst, R., Koay, K. L. (2008). “Avoiding the uncanny valley: robot appearance, personality and consistency of behavior in an attention-seeking home scenario for a robot companion,” *Autonomous Robots* 24(2): 159-178.

Waters, E., Sroufe, L. A. (1983). “Social Competence as a Developmental Construct,” *Developmental Review* 3(1): 79–97.

wikipedia.org (2012). “Wii Remote,” Retrieved 3 May, 2012, from http://en.wikipedia.org/wiki/Wii_Remote.

Wiltermuth, S. S., Heath, C. (2009). “Synchrony and cooperation,” *Psychological Science* 20: 1–5.

Wisniowski, H. (2006). “Analog Devices And Nintendo Collaboration Drives Video Game Innovation With iMEMS Motion Signal Processing Technology.” Retrieved 3 May, 2012, from http://www.analog.com/en/press-release/May_09_2006_ADI_Nintendo_Collaboration/press.html.

Wohlschlaeger, A., Gattis, M., Bekkering, H. (2003). “Action generation and action perception in imitation: an instance of the ideomotor principle,” *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* 358(1431): 501–515.

Woods, S., Dautenhahn, K., Schulz, J. (2004). “The design space of robots: Investigating children's views,” *Proc. IEEE Ro-man 2004, 13th IEEE International Workshop on Robot and Human Interactive Communication*. Kurashiki, Okayama Japan, IEEE Press: 47-52.

Woods, S., Dautenhahn, K., Schulz, J. (2005). “Child and adults' perspectives on robot appearance,” *Proc. AISB'05 Symposium on Robot Companions: Hard Problems and Open Challenges in Robot-Human Interaction*. University of Hertfordshire, UK, SSAISB: 126-132.

www.polhemus.com (2009). “LIBERTY Electromagnetic Motion Tracking System,” Retrieved 1 June, 2009, from http://www.polhemus.com.

Yamaoka, F., Kanda, T., Ishiguro, H., Hagita, N. (2005). “’Lifelike’ behavior of communication robots based on developmental psychology findings,” *5th IEEE-RAS International Conference on Humanoid Robots*: 406 - 411