Can Real-time, Adaptive Human-Robot Motor Coordination Improve Humans' Overall Perception of a Robot?

Qiming Shen, Kerstin Dautenhahn, Joe Saunders, and Hatice Kose

***Abstract*—Previous research on social interaction among humans suggested that interpersonal motor coordination can help to establish social rapport. Our research addresses the question of whether, in a human-humanoid interaction experiment, the human's overall perception of a robot can be improved by realising motor coordination behaviour that allows the robot to adapt in real-time to a person's behaviour. A synchrony detection method using information distance was adopted to realise the real-time human-robot motor coordination behaviour, which guided the humanoid robot to coordinate its movements to a human by measuring the behaviour synchrony between the robot and the human. The feedback of the participants indicated that most of the participants preferred to interact with the humanoid robot with the adaptive motor coordination capability. The results of this proof-of-concept study suggest that the motor coordination mechanism improved humans' overall perception of the humanoid robot. Together with our previous findings, namely that humans actively coordinate their behaviours to a humanoid robot's behaviours, this study further supports the hypothesis that bidirectional motor coordination could be a valid approach to facilitate adaptive human-humanoid interaction.**

***Index Terms*—Humanoid robot, Human-humanoid interaction, Motor coordination, Information distance.**

I. Introduction

ONE major aim of Human-Robot Interaction (HRI) research is to enable a human to interact with a robot in a 'natural' manner [1]. 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 [2], [3]. Numerous studies have been performed to investigate how to make robots operate as partners or companions that can be comfortably accepted by humans [1], [4], [5]. One direction is to draw inspiration from human-human interactions and then apply them in HRI [6], [7]. In this study, how interpersonal motor coordination can be used to facilitate human-humanoid interaction is investigated.

A. Motor Coordination in Interpersonal Social Interaction

It has been suggested by past psychological research that socially situated agents tend to coordinate their motor behaviours [8]. According to Bernieri and Rosenthal [9], there are two types of motor coordination: one called *behaviour matching* and the other called *interactional synchrony*. 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 Chartrand and Bargh [10] define as *"non-conscious 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"*. The results of Chartrand and Bargh's experiments validated the existence of the chameleon effect by finding that the participants subconsciously changed their behaviours according to 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.

Van Ulzen et al., [11] have studied automatic synchronization of walking partners' leg movements when they are walking side-by-side and have shown that this can be an instance of interpersonal synchrony both consciously and unconsciously. Wiltermuth and Heath [12] reported that interpersonal synchrony could also benefit the establishment of rapport and could promote cooperation among group members. In addition, Lakin and Chartrand [13] indicated that the desire to create rapport with confederates, in turn, increased individuals' non-conscious mimicry.

All these studies suggest that the interplay between motor coordination behaviours and rapport was positively related (also see LaFrance [14]). It might also exhibit the mutual understanding of the adoption of motor coordination behaviour among interaction partners, although sometimes none of them were 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.

B. Motor Coordination in Human-Robot Interaction

If motor coordination can facilitate interpersonal interaction, can this dynamical process be adopted to improve human robot interaction? Marin et al., [7] proposed that bidirectional motor coordination was a promising direction to enhance a humanoid robot's social competence. They suggested that humanoid robots and humans should mutually influence each other in order to facilitate adaptive human-robot interaction.

Q. Shen, K Dautenhahn and J. Saunders are with the Adaptive Systems Research Group, University of Hertforshire, Hatfield, AL10 9AB, UK. (email: (Q.Shen) sq4aa@hotmail.com, K.Dautenhahn@herts.ac.uk, j.1.saunders@herts.ac.uk)

H. Kose is with the Computer Engineering Departmemnt, Istanbul Technical University, Office No. 3313, Maslak, 34469, Istanbul, Turkey. (email: Hatice.Kose@itu.edu.tr)

The feasibility of bidirectional motor coordination in HRI has been supported by a number of studies. For example, Robins et al., [15] 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. Dautenhahn [16] investigated temporal coordination between a mobile robot and a human and demonstrated a bidirectional adaptation process. In this process, the participant initially adapts his/her behaviour to a pattern that influences the robot's behaviour. The robot then adapted to the participant's behaviour based on the pattern he/she selected. Both Robins' and Dautenhahn's studies indicate that a human will proactively coordinate his/her movements to a robot's behaviour.

In our previous experiments [17], [18], it was also found that humans tended to synchronize their movement rhythm to a humanoid robot's movement rhythm in their interactions. Two experiments were performed to investigate both motor interference and motor coordination. Regarding motor interference, a significant interference effect was found when the participants were interacting with a humanoid robot compared to other stimuli. Furthermore, the experimental results suggested that the participants' beliefs of the engagement of the robot and the use of music might both contribute to the overall perception of the humanoid robot as a 'social entity' and consequently provoke the interference effect in the two experiments respectively. In the motor coordination investigation, participants tended to coordinate their behaviour rhythm to the behaviour rhythm of the humanoid robot. These studies thus suggest that the overall perception of a robot as a social entity may also facilitate motor coordination in human-humanoid interaction.

Inspired by the above research, the core objective of the present study is to further validate the feasibility of bidirectional motor coordination in human-humanoid interaction. We have achieved this by firstly, developing a method that enables a humanoid robot to coordinate its movements to a human in real-time interaction and subsequently, investigated the robot's resulting coordinated influence on the human.

C. The Synchrony Detection Method

In order to realise 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 by the work of Klyubin et al., [19], 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 [20] based on Shannon's information theory [21].

This method calculates the behaviour synchrony between a human and a robot from the spatial and temporal relationships

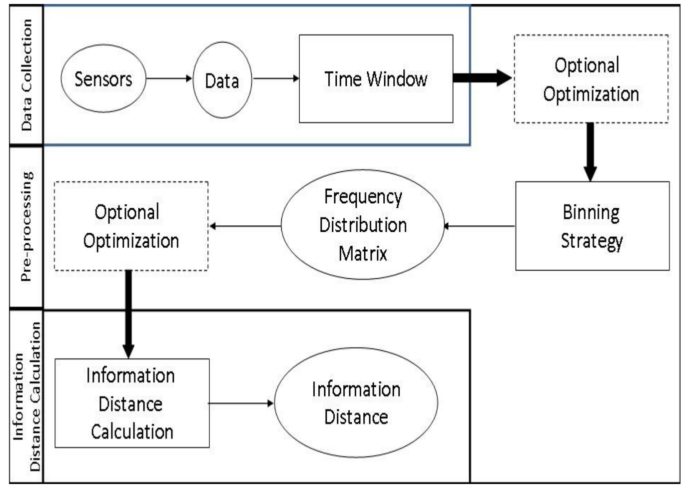

Fig. 1. The information distance methodology general procedure flow chart.

between their movement trajectories. The behaviour synchrony is indicated by the numeric size of the information distance values: low information distance values for synchronized behaviours and high information distance values for unsynchronized behaviours. The general procedure of the information distance method processing the trajectory data collected from a human and a robot to compute their synchronization status is shown in Fig. 1 and Algorithm 1.

According to this general procedure, the trajectories to be compared are firstly collected into a moving time window. For each time step, an information distance value is calculated from the trajectory data stored in the current time window. Next, the time window is updated with new entries of the trajectory data. The collected movement trajectory data of the human and the robot are allocated into different data bins according to their value and the binning strategy. The binning strategy component is then used to extract data distribution features, which potentially reflect the temporal and spatial relationships of the trajectories. The results of this step are a set of data frequency distribution matrices, which are the critical source of information to conduct the information distance calculation. Information distance is calculated between two variables, usually a pair of corresponding behaviour components from the human and the robot respectively (for example, the x-coordinates of the human's hand trajectories and the x-coordinates of the robot's hand trajectories in 3D space). The information distance between two data variables X and Y is defined as the sum of two conditional entropies of these two variables. It can be transformed and calculated using (1) [22].

$$d(X,Y) = 2 * H(X,Y) - (H(X) + H(Y)) \qquad (1)$$

where d(X,Y) is the information distance between variable X and Y; H(X,Y) is the joint entropy of X and Y; H(X) and H(Y) are the entropies of variable X and Y respectively. The values of H(X,Y), H(X) and H(Y) can be calculated from the data frequency distribution matrix. If the trajectories are in 3D space, the overall information distance is the average of the information distance of the x, y and z dimensions.

The information distance method has been successfully validated and applied as the synchrony measure in our previous studies concerning motor coordination [17], [18], [23]. Note that in the previous work the information distance values were not used in real-time as part of the interaction, they were only used for the analysis of HRI experiments. The present work takes a significant further step and uses information distance values in order to adapt human-robot interaction in real-time.

One of the advantages of using the information distance approach is that it can capture general relationships between sensors instead of only linear relationships [24]. In studies by Olsson et al., [22], [25] and Mirza's studies [24], the information distance measure outperformed many other measures in tasks such as sensory reconstruction and capturing sensorimotor relationships. 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 addition, our future research may involve 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 our research.

II. EXPERIMENT

A. Research Questions

There are two main research questions posed for this study. The first is related to the realization of motor coordination mechanism on a humanoid robot and the second is related to whether the application of motor coordination behaviour can improve the human participants' overall perception of the humanoid robot:

1) Can the information distance synchrony detection method be used in real-time to help a humanoid robot to coordinate its behaviour to a human's behaviour? If the motor coordination behaviour is successfully realised, the information distance value detected at the end of the human-humanoid interaction is expected to be significantly lower than the information distance value detected at the beginning of the interaction.
2) Will a human prefer a social robot that coordinates its behaviour to match his/her behaviour compared to a social robot that does not coordinate its behaviour to match his/her behaviour? If the motor coordination behaviour can improve the human participants' overall perception of the robot, it is expected to find from the participants' feedback that most of the participants prefer the interaction with the humanoid robot for the coordination condition than the interaction for the baseline condition.

B. Experimental Design

In order to realise the core objective of this study, a human-humanoid interaction experiment was designed with the information distance synchrony detection method adopted as the core part of a motor coordination mechanism for a humanoid robot. Please note that motor coordination in this study is specified to movement speed 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 realised, it might improve humans' overall perception of the robot and consequently facilitate human-humanoid interaction.

In our previous experiments [17], [18], it was found that relatively playful experimental settings (e.g. with the application of music and the usage of behaviours that can be performed easily) as well as participants' beliefs (e.g. making participants believe that they are interacting with a robot that is engaged in the interaction) might improve the participants' overall perception of the robot as a social entity and facilitate human-humanoid interaction. The experiment in the present study was designed and based on these findings. In order to investigate both motor interference and motor coordination, the behaviour patterns adopted in our previous experiments were very simple (participants were instructed to keep the upper arm stationary and wave the forearm either horizontally or vertically, in line with the existing literature [26] on motor interferences effects in human-human and human-robot interaction). This new experiment was only concerned with the investigation of motor coordination, which allowed the introduction of more varied and playful behaviour patterns. Thus, in this study participants were asked to perform a number of simple and continuous hand gesture patterns that were easy for both a human participant and a robot to produce. The hand gesture patterns were required to be continuous and periodic so that the patterns performed by the humans and the robot could be used for behaviour synchrony analysis. In addition, the humanoid robot used in this study was designed to give instructions to participants using speech, which may facilitate the participants' beliefs that the robot was engaged in the interaction with them. Using speech output might also make the interaction more playful and enjoyable.

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 speed synchrony between the participants and itself using the synchrony detection method and adjusted its movement speed according to the synchrony information. Thus, the robot might gradually coordinate its own speed to match the participants' speed. In the actual experiment, there was also a baseline condition that the humanoid robot did not coordinate its movement speed to the participants' movement speed. Instead, it always performed its movements using a constant speed. After the experiment, participants were asked to fill a questionnaire to provide their feedback to the experiment. The experimental results and feedback of the participants for the coordination condition and baseline condition were compared and analyzed

Fig. 2. Experimental layout: in the human-humanoid experiment, a participant was instructed to stand in front of KASPAR2 and hold a Wii Remote to perform a gesture pattern. The trajectories produced were projected onto the body of KASPAR2 using a projector.

to evaluate the impact of the motor coordination mechanism

C. Humanoid Robot Platform

The humanoid robot adopted in this study 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. In this study, KASPAR2 uses its right arm to perform gesture patterns. It also has a speech module to give instructions to the participants. The application of gesture and speech on the robot may make the interaction more interesting and encourage the participants to get involved in the interaction with the robot. KASPAR2 is shown in Fig. 2.

D. Participants

Twenty-three right-handed participants participated in the experiment, with an age range from 22 to 52 years. Nineteen participants were recruited from staff and students at the University; four were recruited from professionals working in different industries. All participants were naive with respect to the purpose of the experiment. This research was approved by the University of Hertfordshire's ethics committee for studies involving human participants. Informed consent was obtained in writing from all participants in the study.

E. Gesture Patterns

Three gesture patterns were adopted in the present experiment: infinity, circle and triangle (shown in Fig. 3). According to the requirements stated in the 'Experimental Design' section, the selected gesture patterns should have two main attributes: simple and continuous. The patterns shown in Fig. 3 satisfy those two requirements.

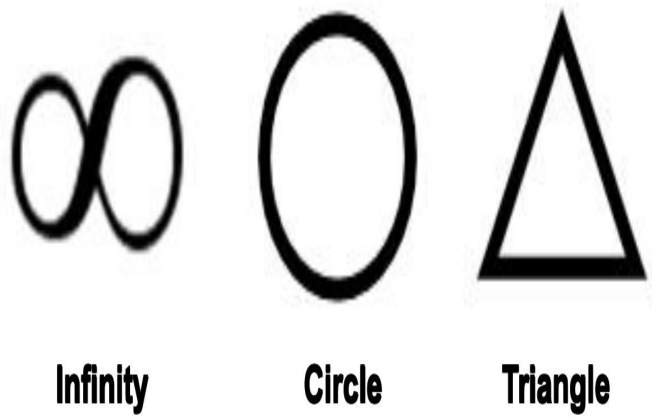

Fig. 3. Designed gesture patterns: infinity, circle and triangle.

F. Speech Module

The speech function of the robot in this experiment was realised 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 [27].

G. Gesture Interaction and Data Collection

In order to realise 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 toolkits and libraries were employed.

In the experiment, the participants were required to stand opposite to and facing the robot at a distance of about 1.5 meters, while holding and using a Wii Remote [28] to perform the gesture patterns (the Wii Remote is shown in Fig. 4). A Wii Remote is a motion controller manufactured by Nintendo [29]. 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 [30]–[33]. 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' [34] 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' and 'B' buttons were mapped as the left and the right buttons 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.

Fig. 4. The Wii controller used used in the experiements.

Apart from the WiinRemote toolkit, an open source pattern recognition library, AME Patterns library [35], was also utilized in the experiment to realise 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.

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 (see Fig. 2), 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 projected participants' hand gesture trajectories (via using the Wii Remote and the WiinRemote toolkit) on the computer screen were captured by the AME Pattern library interface for pattern recognition. These trajectory data were also sent to the humanoid robot as the human part of the input to the information distance method. The robot part of the input to the information distance method was obtained from the robot hand gesture trajectories based on the internal servo readings of the humanoid robots

Other input from the Wii Remote, such as the confirmation information, was also collected and sent to the humanoid robot together with the results of the hand gesture pattern recognition from the AME Pattern library. These data were processed by the robot and then it could make appropriate reactions to the participants' behaviours in the human-humanoid interaction.

Please note that the information distance method is a generalized method, which can process input from not only the Wii Remote but also from, for example, the visual scene. In our previous studies [17], [23], we validated the effectiveness of this method in human-humanoid interaction using input obtained from the visual scene with the help of a marker detection technique, ARToolkit [36]. The information distance method could successfully indicate the synchronization status of a human and a robot in real-time when the input data were obtained from the visual scene (this was validated in internal tests but has not been applied in user studies). However, when using the marker detection technique it took much longer to train participants to manipulate the markers properly (as compared to using the Wii Remote). Inappropriate manipulation of the markers may result in a lot of noise in the input as the marker detection technique is sensitive to light conditions. As a preliminary step to realise real-time motor coordination in human-humanoid interaction, we adopted a more reliable and convenient approach to collect the input data. Therefore, in this study, we used the Wii Remote instead of the visual scene to collect data. In our future research, we may choose to obtain input from the visual scene instead of the Wii Remote, but it was not necessary for answering the research questions of the present study.

H. *The Information Distance Algorithm*

Algorithm 1 shows the pseudo code for the information distance algorithm. In this work the time sliding window was set to hold a 55 frames (or time steps) of data and the frequency for obtaining motion data from the Wii and from the robot was around 15 Hertz. The lag between detection and reaction including processing time was around 3 seconds. Once a frame of human motion data is received, a frame of robot motion data is requested and retrieved to establish the one-to-one correspondence between data from different sources. As the robot motion data is obtained from internal servo readings, there is very little delay between its request and retrieval. The sequence of human motion data transmission was maintained by using a send-acknowledgement mechanism. Together with the processing time for the algorithm the overall processing time was less than 0.07th of a second. The total processing lag of around 3 seconds was considered fast enough to qualify as being 'real-time'. Clearly this could be made faster by either reducing the sliding window size or increasing the rate for obtaining data from the Wii or Robot.

I. *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 coordination trial in which the

Algorithm 1 Information Distance Synchrony Detection

Require: Human and Robot arm trajectories
  while not end of data **do**
    for each data column **do**
      update time window by one data point {*a time window of 55 cells is iterated by one data point*}
      new data points = average(time window)
      tendency = compare(previous data points, new data points){*the tendency of the new data points is calculated by comparing them with the previous data points to examine whether the values of these points are increasing or decreasing. The aim of using tendency in binning strategy is to reduce the impact of delay (or time-shift)*}
      update bin range
      bin interval = average(bin range)
      assign new data points to bins according to value and tendency
    end for
    {*for 2 corresponding data columns X and Y - i.e.human vs.robot arm trajectory update frequency distribution for X, Y and the matrix*}
    for all a in X **do**
      for all b in Y **do**
        if bin value of X == a **then**
          bin frequency array $X[a]$++
        end if
        if bin value of Y == b **then**
          bin frequency array $Y[b]$++
        end if
        bin frequency matrix $[a][b]$++
      end for
    end for
    information distance == average(2*H(X,Y) (H(X) + H(Y))
    {*H(X,Y): joint entropy; H(X) entropy of X; H(Y): entropy of Y*}
  end while
  return Information distance between two trajectories

TABLE I
DETAILED PROCEDURE FOLLOWED BY PARTICIPANTS

In the practice session:
1. Introduction and welcome.
2. Aim of the practice session.
3. Instructions on Wii for performing gestures and confirmations.
4. Prompt to choose pattern and start the practice.
5. Prompt that the pattern is correctly recognized, well done.
6. Prompt to try the next.
7. Prompt the end of the practice.
Shared by both the practice session and the interaction session:
1. Prompt that a pattern has been received.
2. Confirm whether the pattern demonstrated by the robot is the one they intend to perform.
3. or Prompt that no pattern has been received.
4. or Prompt that the pattern is not recognized.
5. or Prompt that no confirmation has been received.
6. or Prompt that the confirmation is not recognized.
7. or Prompt that the participants should only perform one pattern each time.
8. or Prompt that the participants should press button only once for confirmation.
In the Interaction session:
1. At stage 1: prompt to start the interaction session and ask the participants to choose a pattern (prior to the start of the interaction session, the participants have been informed by the human experimenter the sequence of the patterns to choose).
2. At stage 2: prompt movement illustration and ask the participants not to perform any action at this stage, instead, perform movements either faster or slower than the demonstrated movements at the next stage.
3.At stage 3: prompt the participants to perform movements together with the robot.
4.At stage 4: prompt the participants to re-perform movements together with the robot and maintain the movement speed they used at stage 3.
5.Prompt the end of session.

robot coordinated its movement speed to match the participant's movement speed. The other was the baseline trial in which the robot performed its arm movements at a constant speed regardless of the participant's movement speed. For each trial, 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 (see table I for detailed sequences). 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. If the participants chose 'Yes' (by pressing a button on the Wii), 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 continued until the time limit was reached.

After the practice trial, the formal interaction trials then followed. The order of appearance of the coordination 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.
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 whether the robot or the participants were moving faster. Thus the general direction of speed coordination, i.e. whether the robot should increase or decrease its movement speed could be ascertained. One point worth mentioning is that the participants were particularly instructed to perform their movements either faster or slower than the robot's movement speed and try to maintain their own movement speed in the next stage of the interaction. This instruction was to avoid two kinds of situation. The first one was that if the participants' movement speed was the same as or very close to the robot's movement speed it would inhibit the motor coordination mechanism functioning. The second situation was that the participants' tired when coordinating their own movement speed to the robot's movement speed during their interaction. Based on the experience from our previous studies, these two situations were very likely to happen without particular instruction. Both situations might result in the effectiveness of the motor coordination mechanism being unable to be fully tested.
4) Coordination/baseline interaction: the final stage was the only difference between the process of the coordination 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 coordination condition, the humanoid robot gradually increased or decreased its movement speed according to the general direction of speed coordination obtained from the third stage until the information distance was reduced to a satisfactory limit or the time limit of the interaction was reached. An empirical value of 1.5 was adopted as the satisfaction limit of this experiment. Various tests performed prior to the present experiment showed that this empirical value was adequate for this task. Please be aware that the satisfaction limit might not always be reached due to the physical limitations 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 maintained 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.

J. Measurements

In this experiment, there were three main quantities taken as 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 to 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 to 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 to as mean-information value). The effectiveness of the motor coordination mechanism was mainly measured by whether the information distance value could be significantly reduced within the coordination 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 coordination condition of the interaction. In addition, the end-information value and the mean-information value for the coordination 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 over a period of time.

K. Questionnaire

Questionnaires are widely used as a tool to measure users' perception of robots in human-robot interaction research [37]–[39]. Due to the lack of commonly agreed standardized questionnaires, many researchers have built their own questionnaires according to the specific 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., [40], which were intended to be used to measure the anthropomorphism, animacy, likeability, perceived intelligence and perceived safety aspects of robots. However, there are still many aspects that need to be addressed 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 complete a questionnaire after the experiment. The main questions were as follows:

1) Q1: How well do you rate KASPAR2's gesture recognition?
2) Q2: How well do you rate KASPAR2's behaviour performance?
3) Q3: How would you rate KASPAR2 in terms of social interaction?
4) Q4: How much did you enjoy the game as a whole?
5) Q5: Which of the two games did you like better?

Questions 1, 2, 3 and 4 were asked twice in the questionnaire for both the coordination condition and the baseline condition. For these four questions, 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). In question 5 participants were asked only once 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 [41], not over-complicating the concepts [40], 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 of interaction with a robot. The application of a rating based feedback system might also encourage random responses when the participants were exhausted [41].

III. Results

A. Experimental Results Analysis

For the experimental results analysis, a repeated-measures 2 (coordination condition) * 3 (gesture pattern type) ANOVA test with three different measurements (start-information value, end-information value and mean-information value) was performed. Significant main effects of coordination were found for the end-information value, $F(1,22) = 88.565$, $p < .001$ and the mean-information value, $F(1,22) = 38.068$, $p < .001$, but not for the start-information value, $F(1,22) = .044$, $p = .835$ (see fig. 5 and table II). In addition, significant main effects of pattern were found for all three measurements: $F(1,21) = 4.107$, $p = .031$ for the start-information value, $F(1,21) = 7.197$, $p = .004$ for the end-information value and $F(1,21) = 7.477$, $p = .004$ for the mean-information value (see fig. 6 and table III). The interaction effect of coordination * pattern was not found to be significant for any of the three measurements, $Fs(1,21) < .296$, $ps > .747$, which indicated that the significant effects of coordination were independent of the selection of gesture patterns. In order to further investigate the effectiveness of the motor coordination mechanism, which was the core objective of this experiment, the paired t-tests were performed to contrast the start-information value and the end-information value for each gesture pattern and for both the coordination 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 coordination condition: $t(22) = 4.076$, $p = .001$ (corrected $\alpha = .017$) for the infinity pattern, $t(22) = 6.227$, $p < .001$ (corrected $\alpha = .017$) for the circle pattern and $t(22) = 9.059$, $p < .001$ (corrected $\alpha = .017$) 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 patterns for the baseline condition, $ts(22) < 1.962$, $ps > .062$ (corrected $\alpha = .017$). The results of the paired t-tests are shown in fig. 7 and table IV.

TABLE II
DATA TABLE FOR FIG:5

Measure	Type	Mean	Std.Dev.	95% Conf.Interval
Start	Baseline	2.24	0.75	1.93–2.55
	Coord.	2.22	0.71	1.93–2.51
End	Baseline	2.34	0.75	2.03–2.65
	Coord.	1.60	0.62	1.35–1.85
Average	Baseline	2.28	0.70	1.99–2.57
	Coord.	1.84	0.57	1.6–2.08

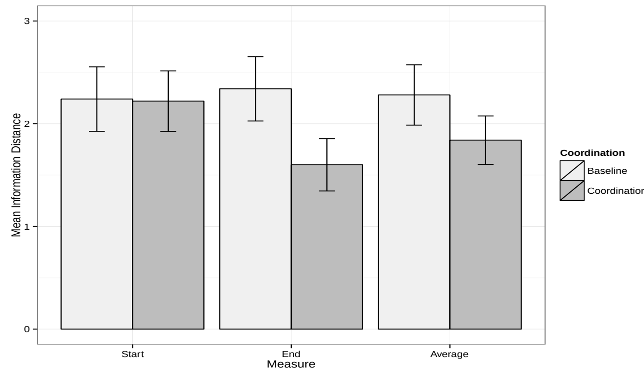

Fig. 5. The comparison of the start-information values, the end-information values and the mean-information values of the performed movements of the participants and the humanoid robot for the coordination condition and the baseline condition of the interaction. Significant differences were found for the end-information and mean-information measurements but not for the start-information measurement in the 2 * 3 ANOVA test. Error bars represent the 95% confidence interval.

B. 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 questions 1, 2, 3 and 4 for the coordination condition and the participants' ratings to the same questions for the baseline condition. The results of the paired t-tests suggested that a significant difference between the ratings of the participants for the coordination condition and that for the baseline condition was only found in Question 1, $t(22) = 2.689$, $p = .013$ (corrected $\alpha = .0125$), but not for questions 2, 3 and 4, $ts(22) < 1.447$, $ps > .162$ (corrected $\alpha = .0125$). Those results are shown in fig. 8 and table V.

For Question 5, fifteen participants (65.2%) selected that they preferred to interact with KASPAR2 in the coordination condition. Four participants (17.4%) selected that they preferred to interact with KASPAR2 in the baseline condition. The other participants (17.4%) did not have any preference or could not tell the difference between the coordination condition and the baseline condition (see Fig. 9). The participants' preference according to the interaction type (coordination / baseline) was statistically analyzed using a one-way Chi-square test. The result of the Chi-square test indicated that the participants' preference for the coordination condition was statistically significant: $\chi^2(1) = 6.368$, $p = .012$ (excluding no preference responses) and $\chi^2(2) = 10.522$, $p = .005$ (including no preference responses) respectively.

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

IV. Discussion

In the $2*3$ ANOVA test of the experimental results analysis, the end-information values and the mean-information values for the coordination condition were found significantly lower than those for the baseline condition. No significant difference was found between the start-information values for the coordination condition and the start-information values for the

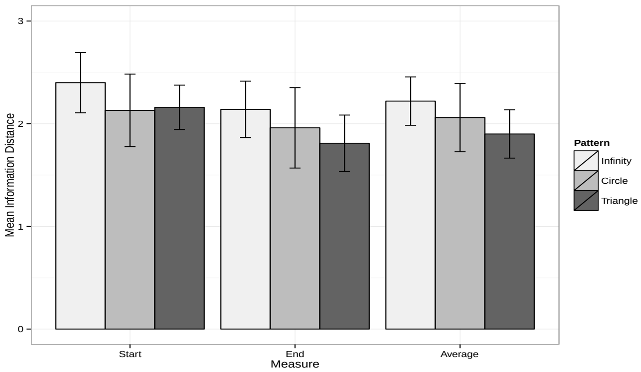

Fig. 6. The comparison of the start-information values, the end-information values and the mean-information values of the performed movements of the participants and the humanoid robot with different patterns (infinity, circle and triangle) in the interaction. Significant main effects of pattern were found for all three measurements in the 2 * 3 ANOVA test. Error bars represent the 95% confidence interval.

baseline condition. Moreover, the end-information values were found to be significantly smaller than the start-information values for the coordination 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 to be significant. Those results together indicated that the information distance level for the coordination condition and the baseline condition were relatively close at the start of the human-humanoid interaction. During the interaction, the information distance level was significantly reduced for the coordination 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 coordination condition and the baseline condition is illustrated in Fig. 10. Therefore, it could be inferred that the behaviour coordination 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

TABLE III
DATA TABLE FOR FIG:6

Measure	Pattern	Mean	Std. Dev.	95% Conf. Interval
Start	Infinity	2.40	0.73	2.11–2.69
	Circle	2.13	0.86	1.78–2.48
	Triangle	2.16	0.53	1.94–2.38
End	Infinity	2.14	0.66	1.87–2.41
	Circle	1.96	0.94	1.57–2.35
	Triangle	1.81	0.68	1.54–2.08
Average	Infinity	2.22	0.59	1.98–2.46
	Circle	2.06	0.81	1.73–2.39
	Triangle	1.90	0.56	1.66–2.14

For the paired t-tests performed for the questionnaire feedback analysis, the difference between the participants' ratings for the coordination 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 questions 2, 3 and 4. The participants rated the performance of the gesture recognition function of the robot for the coordination condition significantly higher than that for the baseline condition, although the exact same gesture recognition module was used in both conditions. 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. Firstly, 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 coordination program, was not a process that was very obvious for the participants to realise. Furthermore, the gesture recognition was one of the most important elements in this

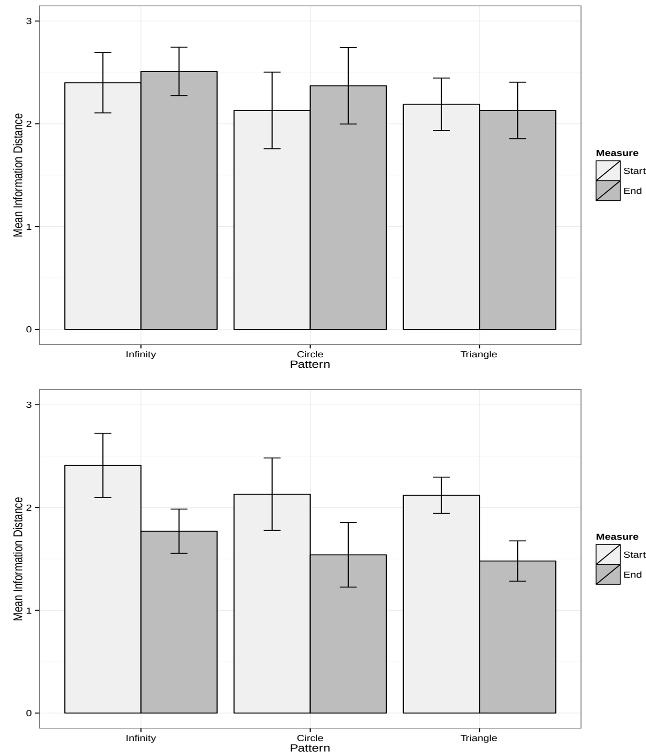

Fig. 7. The comparison of the start-information values and the end-information values of the performed movements of the participants and the humanoid robot with different gesture patterns (infinity, circle and triangle) for the baseline condition and the coordination condition of the interaction (upper graph for the base-line condition and lower graph for the coordination condition). The end-information values were found to be significantly smaller than the start-information values for all gesture patterns for the coordination. Error bars represent the 95% confidence interval.

TABLE IV
DATA TABLE FOR FIG:7

Pattern	Measure	Type	Mean	Std. Dev.	95% Conf.Int.
Infinity	Start	Baseline	2.40	0.71	2.11–2.69
		Coord.	2.41	0.77	2.1–2.72
	End	Baseline	2.51	0.56	2.27–2.75
		Coord.	0.77	0.55	1.55–1.99
Circle	Start	Baseline	2.13	0.89	1.76–2.5
		Coord.	2.13	0.85	1.78–2.48
	End	Baseline	2.37	0.93	2–2.74
		Coord.	1.54	0.77	1.23–1.85
Triangle	Start	Baseline	2.19	0.63	1.94–2.44
		Coord.	2.12	0.42	1.94–2.3
	End	Baseline	2.13	0.68	1.86–2.4
		Coord.	1.48	0.49	1.28–1.68

TABLE VII
SUMMARY OF SIGNIFICANT EFFECTS.

Analysis	Test Type	Measurement	Effect/Condition name	Significance
Experimental Results	2*3 ANOVA	End	Coordination	**
		Mean	Coordination	**
		Start	Pattern	*
		End	Pattern	**
		Mean	Pattern	**
	Paired t	Start/End	Coordination-Infinity	**
			Coordination-Circle	**
			Coordination-Triangle	**
Questionnaire Feedback	Paired t	Rating	Coordination-Baseline Q1	*
			Coordination-Baseline Q5	**

This table summarizes all the significant effects found in the experiment.
Please note that for the paired-t tests 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 coordination condition.
Start: Start-information value, End: End-information value, Mean: Mean-information value, Coordination-Infinity: using the Infinity pattern for the Coordination condition.
Note: * for significance level $p < .05$, ** for significance level $p < .01$.

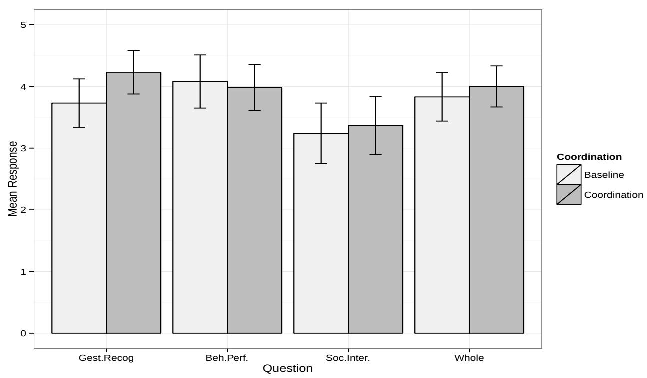

Fig. 8. The comparison of the ratings of the participants to Questions 1, 2, 3 and 4 for both the coordination condition and the baseline condition. A significant difference was found only in Question 1 but not for the rest of the questions in the paired t-tests. Error bars represent the 95% confidence interval.

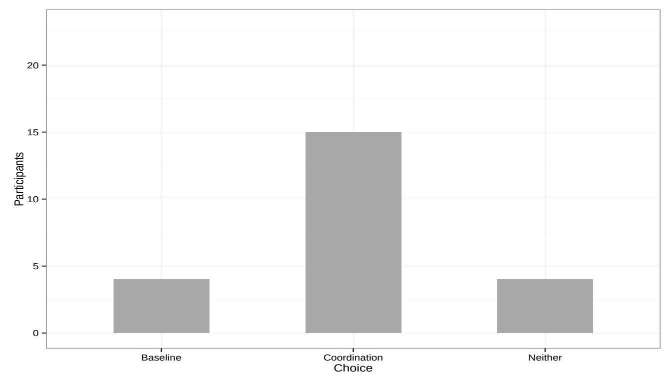

Fig. 9. The participants' preferences in the interaction with KASPAR2 for the coordination condition and the baseline condition.

TABLE V
DATA TABLE FOR FIG:8

Question	Coordination	Mean	Std. Dev.	95 % Conf. Int.
Gest.Recog	Baseline	3.73	0.96	3.34–4.12
	Coordination	4.23	0.85	3.88–4.58
Beh.Perf.	Baseline	4.08	1.04	3.65–4.51
	Coordination	3.98	0.91	3.61–4.35
Soc.Inter.	Baseline	3.24	1.2	2.75–3.73
	Coordination	3.37	1.13	2.89–3.83
Whole	Baseline	3.83	0.98	3.44–4.22
	Coordination	4.00	0.80	3.67–4.33

TABLE VI
DATA TABLE FOR FIG. 9

	Obs.Count	Exp.Count	Std.Resid
Coordination	4.00	7.67	-1.32
Baseline	15.00	7.67	2.65
Neither	4.00	7.67	-1.32

human-humanoid interaction experiment, which might have left a very deep impression on the participants. Consequently, the participants might have inferred 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 coordination condition, they might have chosen a higher rating for the condition that they had better overall experience with. This misunderstanding with regard to the aim of the experiment might also have affected the participants' scores for questions 2, 3 and 4.

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 coordination condition over the interaction with the humanoid robot in the baseline condition, are in line with the above explanation. Moreover, the preference of the participants in Question 5 for the coordination condition suggests that the adaptive motor coordination mechanism using the information distance synchrony detection method could have improved the participants' overall perception of the robot. Since the order of the conditions was counterbalanced, with half of the participants first being exposed to the baseline condition, the order in which individual participants experienced the conditions should not have had an impact on the overall results. Potentially, other factors may have influenced the participants' preference of the coordination condition. Firstly, one may argue that any type of reaction from the robot could have influenced the participants' preference. However, in the

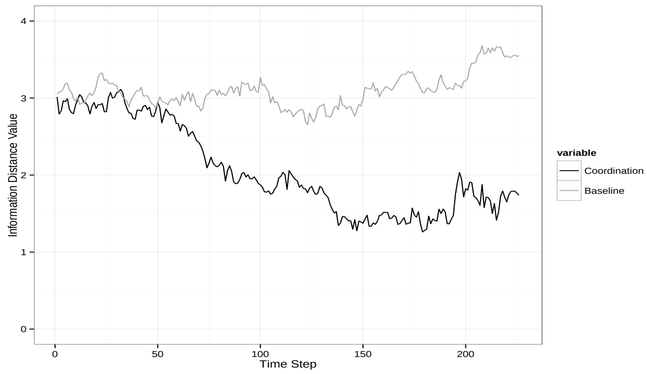

Fig. 10. The change of the information distance level during the interaction between a participant and the humanoid robot for both the coordination condition and the baseline condition.

coordination condition, the robot's behaviour was designed to actively adapt to the participants' movements. If the robot's movement had been contrary to the human's (e.g. the robot moving faster when the participant moves slower or vice versa), one might expect negative perceptions of the robot from the participants. Thus, the coordination and adaptation of the robot's behaviour to the participant's behaviour seems to have been a crucial component contribution the participants' preference of the coordination condition, rather than the mere movements of the robot (the robot moved in both conditions). Secondly, the change of the robot's movement speed was not obvious to a few participants. They could not detect any difference between the coordination condition and the baseline condition, however they still preferred the coordination condition over the baseline condition as they felt "more comfortable" in the coordination phase. This is consistent with the findings in human-human social interaction, namely that motor coordination might facilitate the establishment of liking among humans even when none of them are consciously aware of this process [10]. Therefore, the results of this study suggest that socially appropriate reactions from the humanoid robot to the human interaction partners, such as the motor coordination behaviour, improve the participants' overall perception of the robot.

Apart from the ratings, the participants were encouraged to leave additional comments to explain their decisions of the ratings and their preferences. These comments were voluntary and many participants chose not to leave additional comments after a long period of time of interaction with a robot. Consequently, the qualitative data presented in the questionnaire was not enough to make a fair comparison. Overall, the questionnaire results regarding Q1 and Q5 support the hypothesis that the participants' overall perception of the humanoid robot could be improved by using the motor coordination behaviour. However, results from Q3 ("How would you rate KASPAR2 in terms of social interaction?") do not provide sufficient support for the hypothesis that motor coordination improves the participants' perception of the social competence of the robot, a point that requires further investigation. One may argue that the results for questions Q4 and Q5 are contradictory. However, there was a significant difference between questions Q4 and Q5. In Q4 the participants were asked "How much did you enjoy the game as a whole?", which is a general question about game experience and does not specify what aspects of the game should be judged. That is, the scores the participants gave might not necessarily reflect their judgement of the robot's coordination behaviour. Instead, the participants may have compared the present interaction game with other games that they had had experience with, e.g. a Wii-based video game or even a roller coaster ride. If that was the case, then the differences between the two conditions of the present interaction game compared with other types of games were probably considered relatively small. This might explain why the participants did not differentiate between the two conditions in terms of game experience in their answers to question 4. In contrast, Q5 specifically asked for a comparison of the two conditions ("Which of the two games did you like better?") and answers given to this question, in our view, provide a better indication of the participants' preferences.

Clearly in human adaptive co-ordination there is a bi-directional effect whereby both parties adapt to each other. In our experiments the robot was programmed to adapt to the human participant, but the human was effectively asked not to adapt (by keeping their movement speed constant). We appreciate that this may have unconsciously constrained the human partner and it would be interesting to gauge whether this had a material effect. We would speculate that the interaction would be more fluid and perceived to be more favourable if unconstrained movements were possible, and such experiments would be interesting work for future studies in this area.

Overall, we believe our results give support to our initial expectations, namely that realizing the adaptive motor coordination mechanism on a humanoid robot improved the participants' perception of the robot. Responses to the questionnaires indicated that the experimental scenario and programming of the robot all worked as planned and invoked from the participants generally positive responses and most were happy with the social cues that the robot employed throughout the experiment.

For HRI this implies that robot designers should take into account adaptive co-cordination between the robot and the human partner. Although we have carried out the current experiment on a humanoid robot the equivalent could be achieved for example in a service robot by 'staying in step' with its human partner, or co-ordinating gaze appropriately. Such mechanisms would help robots to become more socially accepted and increase empathy. Recent work in these fields has demonstrated such effects [42]–[44] and provide insights into how such co-ordination effects can be designed.

V. Conclusion

In this study, an experiment was performed to demonstrate the realization of a motor coordination mechanism on a humanoid robot and investigate the effectiveness of this mechanism in real-time human-humanoid interaction. The study represents a first proof-of-concept study on robot to human real-time adaptation implementing motor coordination using information distance. The results of the experiment indicated that the humanoid robot with the motor coordination mechanism was capable of coordinating its behaviour to the participants' behaviour. The information distance synchrony detection method was applied as the core part of the motor coordination mechanism of the humanoid robot. The results of the experiment 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 behaviour than with the humanoid robot without this behaviour, which might suggest that the application of motor coordination behaviour improves the participants' overall perception of the humanoid robot. Future studies need to provide further support for this approach. Moreover, the findings of this study highlight the feasibility and importance of bidirectional motor coordination in human-humanoid interaction.

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Dr. Qiming Shen received his Masters degree in Artificial Intelligence from the University of Hertfordshire, UK in 2006 and his PhD in 2013 . During his PhD study, he participated the EU Integrated Project RobotCub and developed a novel approach to measure behaviour synchrony using information distance. His research interests include motor interference, motor coordination and imitation behaviour development in human-robot interactions. Qiming is currently a Research Scientist in the Advanced Distributed Machine Learning Labs of Essex Lake Group, LLC.

Kerstin Dautenhahn is full Professor in the School of Computer Science at University of Hertfordshire in U.K. where she coordinates the Adaptive Systems Research Group. She received her Ph.D. degree from University of Bielefeld, Bielefeld, Germany, in 1993. She has published more than 300 research articles on social robotics, human-robot interaction, assistive technology and Artificial Life. Prof. Dautenhahn has edited several books and frequently gives invited keynote lectures at international meetings. She has been Principal Investigator of a number of European and nationally funded projects. Prof. Dautenhahn is Founding Editor in Chief of the journal Interaction Studies: Social Behaviour and Communication in Biological and Artificial Systems, as well as Associate Editor of several other international journals. She is Senior Member of IEEE.

Dr. Joe Saunders is a Senior Research Fellow in the Adaptive Systems Research Group of the University of Hertfordshire (UH), UK. He has carried out research in a number of European projects concerned with robot adaptation and learning at both a physical and linguistic level and has operated as lead researcher in these areas. He is especially interested in applying theoretical studies to practical real-world environments and has recently been carrying out trials on robot teaching as part of the EU ACCOMPANY project.

Dr. Hatice Kose is an Assistant Professor in the Computer Engineering Department of Istanbul Technical University, Turkey. She received her MS and PhD degrees from the Computer Engineering Department, Bogazici University, Turkey, in 2000 and 2006, respectively. During her MSc and PhD studies, she worked in several research projects involving vision, localization and multi-agent planning in robot soccer, as well as working as a Teaching Assistant and Instructor in Bogazici University, Turkey. Subsequently, she worked as a Research Fellow at the University of Hertfordshire, UK, in the European 6th Frame Project RobotCub, until 2010. Her work focused on gesture communication and imitation in child-sized humanoid robots. Currently, her research interests include autonomous mobile robots, social robotics, interaction, communication and imitation in artificial systems and robotics