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The Influence of Visual Information on the Motor Control of Table Tennis Strokes

Abstract

Theories of social interaction (i.e., common coding theory) suggest that visual information about the interaction partner is critical for successful interpersonal action coordination. Seeing the interaction partner allows an observer to understand and predict the interaction partner's behavior. However, it is unknown which of the many sources of visual information about an interaction partner (e.g., body, end effectors, and/or interaction objects) are used for action understanding and thus for the control of movements in response to observed actions. We used a novel immersive virtual environment to investigate this further. Specifically, we asked participants to perform table tennis strokes in response to table tennis balls stroked by a virtual table tennis player. We tested the effect of the visibility of the ball, the paddle, and the body of the virtual player on task performance and movement kinematics. Task performance was measured as the minimum distance between the center of the paddle and the center of the ball (radial error). Movement kinematics was measured as variability in the paddle speed of repeatedly executed table tennis strokes (stroke speed variability). We found that radial error was reduced when the ball was visible compared to invisible. However, seeing the body and/or the racket of the virtual players only reduced radial error when the ball was invisible. There was no influence of seeing the ball on stroke speed variability. However, we found that stroke speed variability was reduced when either the body or the paddle of the virtual player was visible. Importantly, the differences in stroke speed variability were largest in the moment when the virtual player hit the ball. This suggests that seeing the virtual player's body or paddle was important for preparing the stroke response. These results demonstrate for the first time that the online control of arm movements is coupled with visual body information about an opponent.

1 Introduction

When humans interact with the world, they coordinate their body movements in real time based on sensory information about their environment (Bootsma & Vanwieringen, 1990; Grierson, Gonzalez, & Elliott, 2009; McBeath, Shaffer, & Kaiser, 1995; McLeod & Dienes, 1993; Sarlegna & Blouin, 2010). For example, baseball players adjust their catching behavior to disturbances of the baseball's flying trajectory induced while they are catching

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the ball (Fink, Foo, & Warren, 2009). Other evidence for real-time action coordination comes from the observation that humans adjust their arm movements to disturbances of the object position induced while they are grasping an object (Reichenbach, Thielscher, Peer, Bulthoff, & Bresciani, 2009). Moreover, control laws describe how the central nervous system continuously converts sensory inputs into motor outputs (e.g., reviews by Turvey, 1990; Warren, 2006). These studies suggest a close link between visual information and the online control of motor movements when humans interact with physical objects.

In everyday life situations, humans do not exclusively interact with physical objects (object interaction); very often they also interact with other humans (social interaction); for example, handing over objects, playing games, or carrying a sofa together. The effect of visual information on motor control has been systematically investigated in object interaction tasks (Reichenbach et al., 2009). However, relatively little is known about the effect of visual information on motor control in social interaction tasks (Georgiou, Becchio, Glover, & Castiello, 2007). An investigation into the relevant sources of visual information for social interaction tasks would provide important insight into the mechanisms underlying the human ability to anticipate observed actions in order to facilitate the performance of social interactions.

Previous research provides evidence that humans are able to use visual information about another person to improve their performance on various tasks. For example, seeing an opponent's body or interaction tool (i.e., a paddle or racket) improved ball prediction performance in table tennis (Streuber, Knoblich, Sebanz, Bulthoff, & de la Rosa, 2011), tennis (Huys et al., 2009; Mann, Abernethy, & Farrow, 2010), squash (Abernethy, 1990), soccer (Savelsbergh, Williams, Van der Kamp, & Ward, 2002), and basketball (Aglioti, Cesari, Romani, & Urgesi, 2008; Sebanz & Shiffrar, 2009). Most of the previous research found that experts (as compared to novices) are superior in predicting the fate of observed actions (Aglioti et al., 2008; Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005; Casile & Giese, 2006; Keller, Knoblich, & Repp, 2007), although nonexperts have the ability to understand the actor's expectations (Runeson & Frykholm, 1983) and intentions (Barrett, Todd, Miller, & Blythe, 2005; Grezes, Frith, & Passingham, 2004). Therefore, one might hypothesize that the behavior of nonexperts in social interactions might not be affected by visual information about another person.

However, some research suggests that visual information about another person influences the movement kinematics of nonexperts in a social interaction task. We define task performance as a measurement of human behavior in a given task at a specific point in time (e.g., the accuracy with which a participant gives a certain judgment at the end of an experimental trial) while movement kinematics are spatial-temporal measures of human limb movements (e.g., the velocity profile of an action). For example, Schmidt, Carello, and Turvey (1990) showed that two participants who were instructed to do cycling leg movements in an out-of-phase manner relative to each other, suddenly shifted to an in-phase leg movement. Since participants had only visual information about the other person available, these results suggest that visual information about the other person affects movement kinematics in naïve participants. Overall, this research suggests that visual information about another person affects movement kinematics but less so for the performance of nonexperts (Schmidt et al., 1990).

To our knowledge, the effect of visual information on movement kinematics and task performance has not yet been compared within the same task. The result (that visual information about another person affects nonexperts' movement kinematics but not their task performance) could also be attributed to other factors, for example, varying task difficulties across studies. Therefore, in the present study, we sought to examine the effect of visual information about another person on the movement kinematics of nonexperts and task performance within the same task.

The examination of the degree to which visual information about another person translates into differences in movement kinematics and task performance aids the understanding of how visual information and motor control are linked when nonexperts perform social interaction tasks. This present study goes beyond previous research in three important aspects. First, we compare the effect of visual information on movement kinematics and task performance within the same task. Previous studies mainly focused on the investigation of either movement kinematics or task performance (e.g., Bideau et al., 2004; Craig, Berton, Rao, Fernandez, & Bootsma, 2006; Fink et al., 2009; Schmidt et al., 1990). An examination of how movement kinematics and task performance are altered by visual information requires that both are examined within the same task. Second, we are interested in the effect of visual information on task performance and movement kinematics under high-fidelity realistic social interaction conditions. Hence, unlike previous studies on movement kinematics that examined the rhythmic movements of participants, the present task did not involve cyclic movement but a more natural social interaction task, namely, table tennis. Third, we varied the availability of different sources of visual information. Previous research suggests that not all sources of visual information are equally effective for social interaction performance (Streuber et al., 2011). Hence, in order to determine the visual variables important for motor control, and consequently for social interaction performance, we varied the availability of different sources of visual information about the interaction partner and the ball.

In order to systematically investigate the effect of visual information on movement kinematics and task performance, we designed a virtual reality table tennis experiment in which participants were asked to respond to table tennis strokes performed by a virtual table tennis opponent. The virtual table tennis opponent was a computer-generated avatar who randomly executed one out of 12 different table tennis strokes, which were prerecorded with a motion capture system and played back as animations to the participant via a head-mounted display (HMD). The experiment was conducted in an immersive interactive virtual environment (IVE) using an HMD and motion tracking of the participant's head and table tennis paddle. The participant's task was to hit the virtual ball stroked by the virtual opponent as naturally and accurately as possible while visual information about the ball, the paddle, and the body of the opponent player were manipulated. This setup allowed us to provide a close-to-natural interaction of the participant with his or her environment while at the same time it gave us full control over the manipulation of the visual information available to the participant. Additionally, the motion tracking of the table tennis paddle allowed an analysis of participants' movement kinematics and task performance. Importantly, we applied all manipulations of the visibility of the ball, the paddle, and the body of the virtual opponent to all 12 prerecorded animations in exactly the same way. As a result, the observed differences between the different visibility manipulations cannot be attributed to specific movement patterns or other characteristics of the virtual opponent. We used task performance and movement kinematics as dependent variables as derived from the motion capture data of the participant's paddle.

Task performance was defined as the minimum distance between the center of the paddle and the center of the table tennis ball throughout the movement trajectory of a participant's table tennis stroke (hereafter simply referred to as the radial error). Note that the link between radial error and hitting performance is given by the fact that a ball would be missed (e.g., not hit) if the radial error exceeds the size of the table tennis paddle. We preferred radial error over a binary coding of performance (e.g., hit vs. nonhit) because radial error is a continuous and therefore a more sensitive measure of performance than a binary measure. Radial error was used in previous studies in order to measure behavior in interceptive sports (Vignais et al., 2010).

Movement kinematics was measured in terms of stroke speed variability. Stroke speed variability was the variability of the speed profiles (speed over time throughout the stroke) of repeatedly executed strokes (see Section 2.4 for a detailed description of how stroke speed variability was derived from the 3D recordings of the participant's paddle). We choose stroke speed variability over the actual 3D movement trajectory as a movement kinematics measure for the following reason. 3D movement trajectories were expected to be very noisy in our experiment since the 12 prerecorded ball trajectories required participants to conduct quite different stroke patterns due to directional changes of the strokes (e.g., striking to the left or right when the ball flew to the left or right side of the participant, respectively). This variability of the stroke patterns would have added additional noise to the data during the analysis, thereby reducing the power of the statistical analysis. Note that the first temporal derivative of the movement trajectory and its associated variability (i.e., stroke speed variability) is less sensitive to the directional changes of the stroke patterns. We therefore chose stroke speed variability over 3D movement trajectories as a kinematic measure.

We hypothesized that if visual information about the other person influences task performance, then we would expect to find significantly different radial errors for conditions in which the ball, the table tennis paddle, and the body of the virtual opponent are visible as opposed to invisible. Likewise, if visual information about the other person or the ball has an effect on movement kinematics, we would expect to find significantly different stroke speed variability between the conditions when the ball, the paddle, and the other person's body are visible as opposed to invisible.

2 Method

2.1 Participants

Ten participants performed the experiment (mean age: 25.6; *SD*: 2.12; 5 females). All participants had normal or corrected-to-normal vision and were right-handed. Participants were recruited from the Max Planck Institute subject database and were naïve with respect to the purpose of the study. This research was performed in accordance with the ethical standards specified by the 1964 Declaration of Helsinki. All participants gave their informed consent prior to the experiment and were paid 8 Euro/hr for their participation.

2.2 Stimulus and Apparatus

Participants played table tennis within the virtual environment (VE). The VE consisted of a virtual table tennis table (standard size: 2.74 m long × 1.525 m wide × 0.76 m high, with a 15.25-cm high net in the middle) and 12 animations of table tennis strokes (see Figure 1 for the 12 different ball trajectories). The animations included a virtual table tennis player, holding a standard table tennis paddle (physical radius of ∼8 cm) and a virtual table tennis ball (40 mm diameter). The movements of participants were tracked using 16 infrared cameras (Vicon MX-13, using Vicon Tracker 1.1 tracking software, 120 Hz) that tracked 10 infrared-reflecting markers rigidly attached to the participant's head and to the participant's paddle. Participants saw a stereoscopic image of the VE through the HMD (nVisor SX60) from an egocentric perspective. The nVisor SX60 has a vertical FOV of 35 and a horizontal FOV of 44 with a resolution of 1280×1024 per eye. Participants also saw a virtual representation of the paddle in their hand. Figure 3 shows one participant wearing the head-mounted display and holding the paddle.

2.3 Animations

The animations were recorded from the body movements of an actor performing table tennis strokes using motion capture technology (see Figure 2). The actor was an athletic female (1.66 m, 20 years old, Division I college athlete) with no major table tennis experience. In order to obtain the animations, the actor was instructed to perform 12 different table tennis strokes. The actor was holding a paddle and was standing at the end of the table. A second person (not recorded by motion capture) stood at the opposite side of the table. The second person threw table tennis balls to the actor's side of the table. Six balls were thrown to the right and six balls to the left side of the table. If the ball was thrown on the right side, the actor responded with a forehand stroke, otherwise with a backhand stroke. Half of the balls the actor stroked to the right and the other half to the left side of the opposite side of the table. All 12 strokes were motion captured using the motion capture system. The cameras recorded 46 (24 for upper body and 22 for lower body) infrared markers which were attached to the body of the actor, five markers which were attached to the paddle, and the table tennis ball was painted with material that reflects infrared light. The painting of the table tennis ball had no noticeable effects on its physical properties. The motion capture data were postprocessed using the Vicon IQ 2.5 software. Missing parts of the ball trajectories (120 fps) were

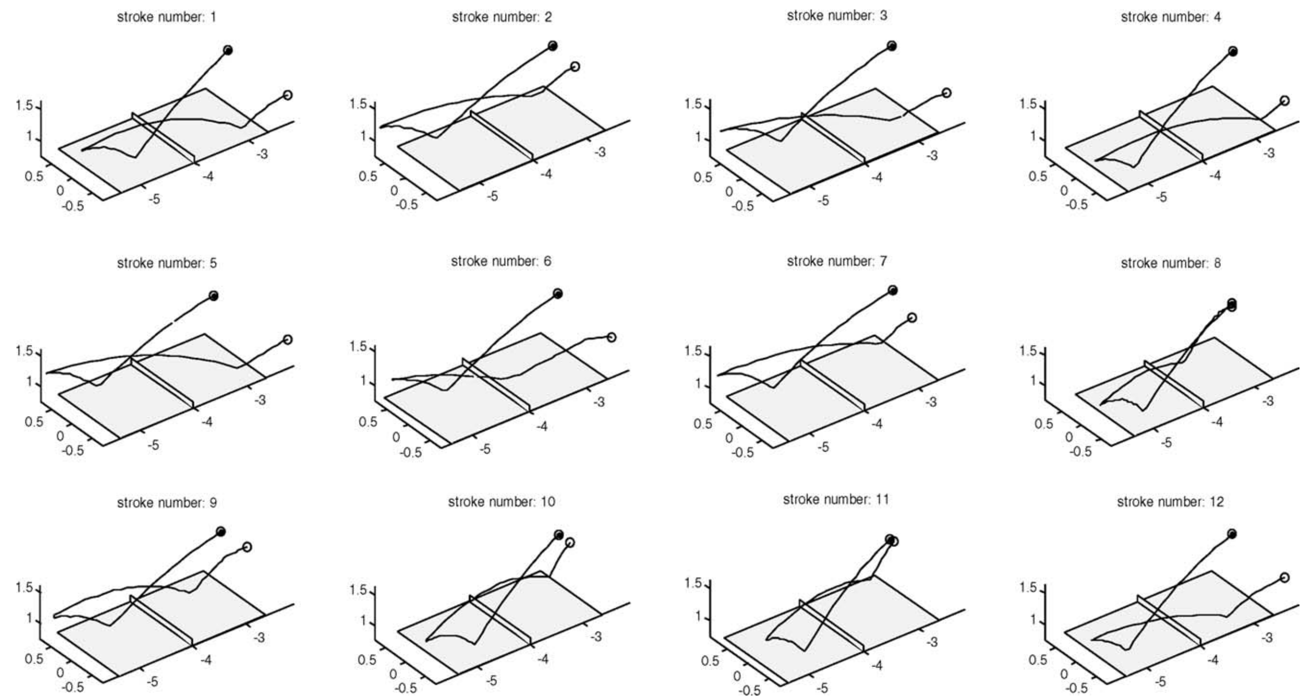

Figure 1. *A visualization of the 12 different ball trajectories. The ball starts its trajectory from the participant's side (black filled dot on the right) toward the virtual player's side (left side). Then the virtual player returns the ball toward the participant who has to hit the ball. The black circled dot indicates the end of the ball trajectory. Six of the ball trajectories were played backhand (numbers 2, 3, 5, 6, 7, and 9) and the other six forehand (numbers 1, 4, 8, 10, 11, and 12) by the virtual player. Additionally, six of the ball trajectories where played to the left side of the participant (2, 7, 8, 9, 10, and 11) and six trajectories where played to the right side of the participant (number 1, 3, 4, 5, 6, and 12).*

fixed using a Vicon IQ 2.5 kinematic fitting filter (less than 1% of the frames were missing). Furthermore, markers on the actor and paddle were automatically labeled by the Vicon objects (actor and paddle) and hand-corrected when necessary. The skeletons (vsk-files) and the animations (v-file) were exported. These files were imported into the Autodesk MAYA animation software (we used the code provided by Carnegie Mellon University for the import).[1]

Finally, these skeletons were attached to a character model (Complete Character set, Rocketbox Studios GmbH), to a ball model, and to a model of a paddle. Finally, the whole animation was exported to Virtools 4.1 (using the Virtools exporter from Dassault Systems). These steps were repeated for all 12 stroke animations. Figure 2 shows the 12 different ball trajectories for the 12 different stroke animations used for all experimental conditions.

1. http://mocap.cs.cmu.edu/tools.php

2.4 Design

The effect of visibility on movement kinematics and task performance was investigated in eight experimental conditions as outlined in Figure 4. We manipulated visual information about the virtual player's body (visible vs. invisible), the virtual player's paddle (visible vs. invisible), and the ball (visible vs. invisible) in a fully crossed $2 \times 2 \times 2$ factorial design. The dependent variables measured movement kinematics and task performance. Task performance was measured in terms of radial error. Radial error was defined as the minimum distance between the center of the paddle and the center of the ball throughout the stroke. Movement kinematics was measured in terms of the variability in speed of repeatedly executed strokes (see Figure 5). Speed profiles

Figure 2. *A visualization of three frames of one of the 12 different table tennis stroke animations. The animations (left) were created by using motion capture data from an actor performing table tennis strokes (right). All 12 strokes were motion captured using a VICON motion capture system with 16 infrared cameras. The cameras recorded 46 (24 for upper body and 22 for lower body) infrared markers that were attached to the body of the actor, five markers that were attached to the paddle, and the table tennis ball, which was coated with infrared reflective paint.*

Figure 3. *Photograph of a participant holding the paddle and wearing the HMD. Participants had to hit the virtual table tennis balls seen as a stereoscopic image within the HMD. The motion trajectory of the paddle was recorded and analyzed.*

(speed over time throughout the stroke) were calculated for each stroke from the 3D motion capture recordings of the participant's paddle (center of the paddle; see Figure 6[a]). The standard deviation profiles from the mean speed profiles were calculated for each condition and participant (see Figure 6[b]). Finally, the standard deviations from the mean were integrated over time (from the moment the animation started to the moment the participant hit the ball). The sum of standard deviations is taken as a measurement of how consistently strokes were executed. Note that if a person were to hit the ball with exactly the same speed profile, then the stroke speed variability would be zero. If the ball were to intercept the center of the paddle, then the radial error would be zero.

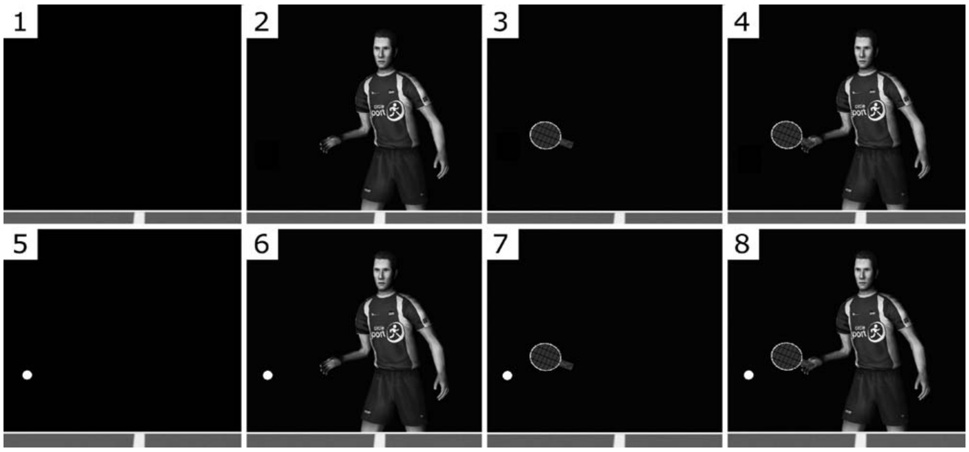

Figure 4. *Visual stimulus for the eight different experimental conditions. We manipulated the visibility of the ball (visible vs. invisible), the paddle (visible vs. invisible), and the body of the virtual player (visible vs. invisible).*

2.5 Procedure

Participants were placed in the middle of the tracking hall and were equipped with an HMD and a paddle. Participants were instructed to hit the ball that was served by the virtual player as naturally and accurately as possible. Participants were not instructed to hit the ball back to the virtual player. Before the experiment started, participants completed a practice block to familiarize themselves with the VE equipment and the task. In this practice block, participants hit virtual static balls that were presented at eight different locations above the participant's end of the table. If a ball was hit, a sound was played, the ball disappeared and the next ball appeared at a new location. After successfully hitting eight balls (with a radial error less than 10 cm), the exercise was completed and the experiment was started.

Each participant played four experimental blocks. Each experimental block consisted of the presentation of the 12 animations under each of the eight experimental conditions ($12 \times 8 = 96$ trials). The order of the 96 trials in each block was randomized. Each trial was 2800 ms long, and started with a 400-ms long beep sound to indicate the start of the trial. Afterward one out of 12 animations started playing. In each animation, the ball started flying from the participant's side of the table toward the virtual player's side of the table. Then the virtual player stroked the ball back to the participant who attempted to hit the ball. Visual (text: "HIT" which was placed in the center of the screen for 1 s) and acoustic feedback (500 ms sound) informed the participant when the radial error was below 50 cm. There was no visual or acoustic feedback when the ball was missed. The feedback was purely motivational. Importantly, all strokes were used for data analysis, whether the feedback was provided or not. In order to continue to the next trial, participants were required to move back into the initial body posture (standing in the center with the right arm relaxed so that the paddle was positioned parallel to the right thigh).

3 Results

3.1 Radial Error

First, in order to see whether performance changed with time (e.g., due to learning, unlearning, or fatigue, etc.), an ANOVA was conducted on participants' mean radial error scores with the four repetitive blocks as a factor. The ANOVA revealed no significant effect of block on radial error, $F(9,3) = 1.77$; $p = .176$. Thus, there was no significant learning effect over time and further analysis of mean radial error was collapsed over blocks.

We tested the effect of visibility of visual information on radial error using a completely crossed within-subjects ANOVA with visibility of the *ball* (visible vs. invisible), visibility of the *paddle* of the virtual player (visible vs. invisible), and visibility of the *body* of the virtual player (visible vs. invisible) as factors.

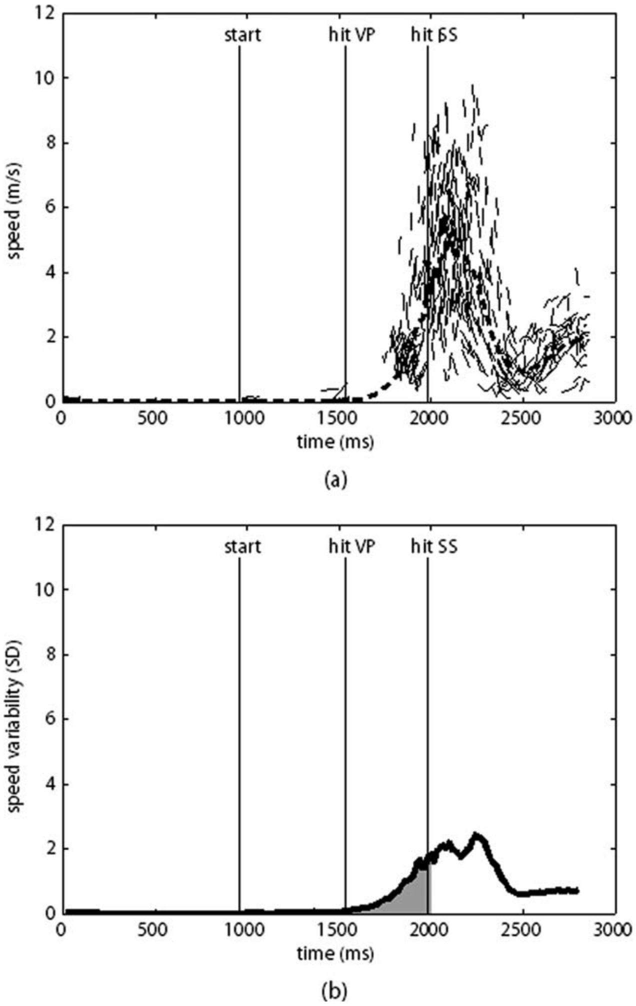

Figure 5. *A visualization of the calculation of stroke speed variability. The 3D trajectory of each stroke (center of the participant's paddle) was recorded with the motion capture system. (a) The 48 speed profiles (thin black scattered lines) and the mean speed profile (thick black scattered line) of one participant in one viewing condition (Condition 8, body, paddle, and ball visible) over the time course of the stroke. The 48 speed profiles were derived from 12 stroke repetitions and four block repetitions. (b) The thick black line indicates the standard deviation from the mean speed profile from (a) over the time course of the stroke (stroke speed variability profile). The left vertical black line (start) indicates the mean point in time when the ball started its trajectory toward the virtual player. The middle vertical black line (VP) indicates the mean time when the virtual player hit the ball. The right black vertical line (SS) indicates the mean time when the participant hit the ball. The overall stroke speed variability was derived by integrating the stroke speed variability profile from the time when the ball started the trajectory (start) to the time when the participant hits the ball (SS).*

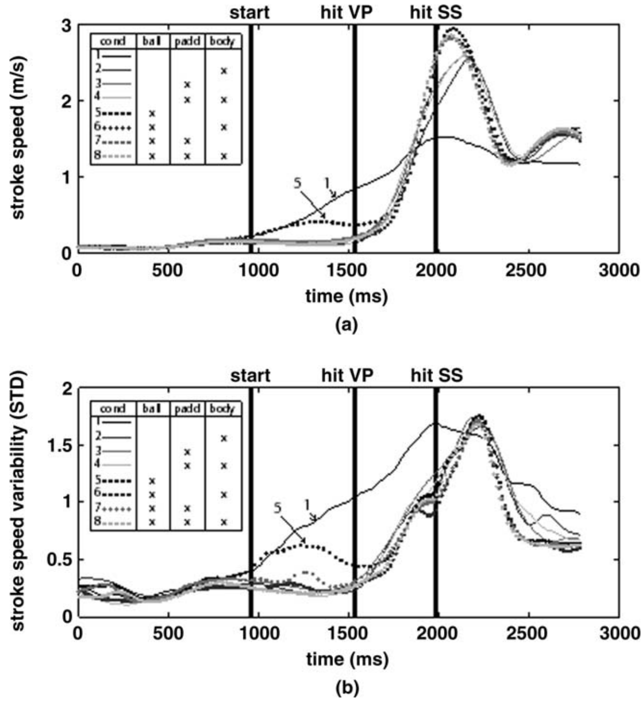

Figure 6. *(a) Stroke speed profiles and (b) stroke speed variability profiles. (a) The average speed profiles of participants' paddle movement over time for each condition. (b) The average standard deviation from the mean stroke speed profiles (stroke speed variability) over time for each condition.* Start *indicates the mean time when the ball starts moving.* Hit VP *indicates the mean time when the virtual player hits the ball.* Hit SS *indicates the mean time when the participant hit the ball. (b) Shows that stroke speed variability was similar in all conditions, except in Condition 1 (where no visual information was available) and in Condition 5 (where only the ball was visible). In these conditions, stroke speed variability was significantly increased. Interestingly, these differences in stroke speed variability had already occurred before the virtual player hit the ball (*hit VP*). The increase in stroke speed variability in Condition 1 remains until the participant hits the ball (*hit SS*). However, the increase in stroke speed variability in Condition 5 disappears after the virtual player hits the ball. In order to do the statistical analysis, the overall stroke speed variability was calculated for each participant and condition by integrating stroke speed variability over time (from* start *to* hit SS*).*

The ANOVA revealed a significant main effect of ball, $F(1, 9) = 200.22$, $\eta^2_{\mathrm{partial}} = 0.957$, $p < .001$, a significant main effect of paddle, $F(1, 9) = 7.42$, $\eta^2_{\mathrm{partial}} = 0.452$, $p = .023$, and a significant main effect of body, $F(1, 9) = 14.31$, $\eta^2_{\mathrm{partial}} = 0.614$, $p = .004$. There was a significant

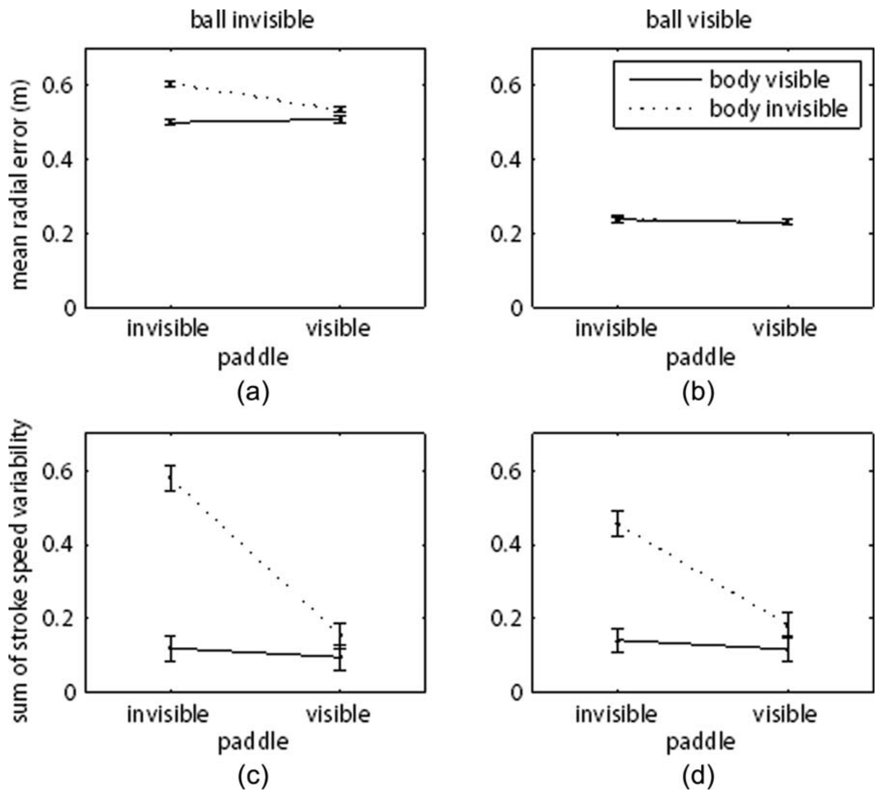

Figure 7. *These graphs show the mean radial error (a, b) and mean stroke speed variability (c, d) coded with respect to the factors ball, paddle, and body. The error bars indicate the standard error from the mean as derived from the error term of the 3-way ANOVA. (a) The significant interaction between paddle and body when the ball was invisible. (b) No effect of paddle and body when the ball was visible. (c, d) A significant interaction between paddle and body that was not modulated by the visibility of the ball.*

interaction between ball and body, $F(1, 9) = 15.00$, $\eta^2_{\text{partial}} = .625$, $p = .004$, and a significant interaction between paddle and body, $F(1, 9) = 8.04$, $\eta^2_{\text{partial}} = 0.472$, $p = .02$. The interaction between ball and paddle was not significant, $F(1, 9) = 4.39$, $\eta^2_{\text{partial}} = 0.328$, $p = .066$. There was also a significant three-way interaction between ball, paddle and body, $F(1, 9) = 10.95$, $\eta^2_{\text{partial}} = 0.549$, $p = .009$. The three-way interaction confirms the statistical significance of the above observation that the ball visible and ball invisible conditions differ with respect to how the factors of paddle and body interact (see Figure 7[a] and 7[b]). We dissected the significant three-way interaction by calculating two separate two-way within-subjects ANOVAs: one for the ball visible and one for the ball invisible condition.

The first ANOVA was run on the subset of the data where the ball was invisible. The ANOVA revealed a significant main effect of paddle, $F(1, 9) = 7.41$, $\eta^2_{\text{partial}} = 0.452$, $p = .024$ and body, $F(1, 9) = 15.86$, $\eta^2_{\text{partial}} = .638$, $p = .003$. The significant interaction between paddle and body, $F(1, 9) = 9.61$, $\eta^2_{\text{partial}} = 0.516$, $p = .013$, is shown in Figure 7(a). Paired t-tests were used to compare the effect of seeing the paddle on radial error depending on whether the body was visible. Seeing the paddle decreased the radial error only if the body was invisible, $t(10) = 3.23$, $p = .010$, but not if the body was visible, $t(10) = 0.69$, $p = .505$. In sum, if the ball was not visible, any information (body and/or paddle information) about the virtual player was helpful in reducing the radial error.

The second ANOVA was run on the data of the ball visible conditions. The ANOVA was conducted to test whether there are significant differences in the radial error depending on the visibility of the paddle and the body of the virtual player. The ANOVA revealed no significant effect of paddle, $F(1, 9) = 2.27$, $\eta^2_{partial} = 0.002$, $p = .166$, no significant effect of body, $F(1, 9) = 0.02$, $\eta^2_{partial} = 0.452$, $p = .894$, and no significant interaction between paddle and body, $F(1, 9) = 0.06$, $\eta^2_{partial} = 0.007$, $p = .813$ when the ball was visible.

In sum, the radial error was always lower when the ball was visible (mean = 0.234 m; $SD = 0.047$) compared to invisible (mean = 0.537 m; $SD = 0.062$). Moreover, the visual information about the virtual player's body and/or the paddle helped only when the ball was not visible.

3.2 Stroke Speed Variability (SSV)

We examined the effect of visual information on SSV in an ANOVA with the within-subject factors: visibility of the *ball* (visible vs. invisible), visibility of the *paddle* of the virtual player (visible vs. invisible), and visibility of the *body* of the virtual player (visible vs. invisible).

The ANOVA revealed a significant main effect of paddle, $F(1, 9) = 28.47$, $\eta^2_{partial} = 0.760$, $p < .001$, and a significant main effect of body, $F(1, 9) = 21.05$, $\eta^2_{partial} = 0.701$, $p = .001$. However, there was no significant effect of ball, $F(1, 9) = 0.86$, $\eta^2_{partial} = 0.087$, $p = .379$. There was also a significant interaction between paddle and body, $F(1, 9) = 26.09$, $\eta^2_{partial} = 0.744$, $p = .001$. However, there was no significant interaction between ball and paddle, $F(1, 9) = 4.23$, $\eta^2_{partial} = 0.320$, $p = .070$. Also, the interaction between ball and body was not significant, $F(1, 9) = 2.27$, $\eta^2_{partial} = 0.202$, $p = .166$. Finally, there was no significant three-way interaction between ball, paddle, and body, $F(1, 9) = 2.52$, $\eta^2_{partial} = 0.218$, $p = .147$. The significant interaction between paddle and body is shown in Figure 7(c) and Figure 7(d). Paired t-tests were used to compare the effect of seeing the body on SSV depending on whether the paddle was visible or not. Seeing the body decreased SSV if the paddle was invisible, $t(10) = 4.92$, $p = .001$, but also if the paddle was visible, $t(10) = 2.49$, $p = .034$. However, seeing the paddle only decreased SSV when the body was invisible, $t(10) = 5.41$, $p < .001$, but not when the body was visible, $t(10) = 1.40$, $p = .195$. In sum, these results indicate that seeing the body of the virtual player always decreased SSV. Seeing the paddle of the virtual player only decreased SSV when the body of the virtual player was not visible. However, the visibility of the ball did not affect SSV. Note that these results complement the results from the analysis of the radial error data. While the radial error data showed that the visibility of the ball leads to the best task performance (in terms of a low radial error), the variability data suggest that movements are carried out in a more consistent manner (in terms of low SSV) if the body is visible. Hence, our analysis of movement kinematics revealed additional aspects that would have gone unnoticed by assessing task performance only.

4 Discussion

This study investigated the role of different sources of visual information on error rate (task performance) and stroke speed variability (movement kinematics). The participant's task was to hit a virtual ball that was played by a virtual table tennis player as accurately and naturally as possible. We found that radial error mainly relied on the visibility of the ball. Furthermore, we found that visual information about the virtual player's body and/or paddle reduced radial error when the ball was invisible. This result is explained by the fact that the ball provides task-relevant information (where the participant's task was to hit the ball). However, visual body and paddle information also provides task-relevant information if the ball is not visible. This suggests that when people are forced to use other visual information to estimate the virtual ball location at the time of stroke, they can do so. Hence, our results extend previous findings that showed that visual information about the other person's body does not induce any performance changes (Vignais et al., 2010). Vignais and colleagues found that the level of graphical detail of a virtual handball thrower did not influence goalkeepers' motor response. In their experiment, handball goalkeepers were asked to stop a ball thrown by a virtual handball thrower with different levels of details: a textured reference level (L0), a nontextured level (L1), a wire-frame level (L2), a point-light-display level (L3), and a point-light-display level where the ball was also a point light display (L4). Performance was measured in terms of radial error, which was the minimal distance between the center of the goalkeeper's hand and the center of the ball when the goalkeeper caught the virtual ball. The authors did not find significant differences in the radial error depending on the level of detail of the virtual thrower (L0 vs. L1 vs. L2 vs. L3), but significant differences depending on the level of detail of the ball (L0, L1, L2, L3 vs. L4). Note, however, that in all conditions, the ball was visible. Our results extend these findings by showing that participants are also able to estimate the ball location from the body and paddle cues if the most task-relevant information (the ball) is not provided.

Our finding that naïve participants can use body and paddle information to improve performance is relevant for theories of action understanding. Previous research suggests that expert players seem to be superior to naïve participants in improving their task performance in the presence of visual information about the other person's body (Abernethy, 1990; Aglioti et al., 2008; Huys et al., 2009; Mann et al., 2010; Savelsbergh et al., 2002; Sebanz & Shiffrar, 2009). This research is less clear about whether naïve participants can use visual information about the other person's body at all. Our finding that naïve participants improved their task performance (i.e., reduced the radial error) when only the other player's body or paddle was visible suggests that nonexpert players also have the ability to anticipate the actions of an opponent if they are forced to do so (i.e., in the absence of visual cues about the ball).

The sensitivity of naïve players to the other person's body and paddle information in our experiment is also indicated by the analysis of the movement kinematics in terms of stroke speed variability. A visual comparison of the average speed profiles suggests that participants started to move earlier when the virtual player was not visible (see Figure 6[a]). The visual inspection of the time courses further suggests that differences in stroke speed variability were largest just before the virtual player hit the ball (see Figure 6[b]). If the body of the virtual player was visible, stroke speed profiles were less variable. Seeing the paddle decreased variability only if the body was invisible. Finally, seeing the ball did not affect stroke speed variability. These results suggest that participants' movements were mainly guided by visual information about the virtual player's body. This result shows, for the first time, that motor movements in nonexpert table tennis players are coupled to visual body information about an opponent. The behavioral differences were largest before and in the moment the opponent hit the ball, suggesting that the participant's behavior was not purely affected by the visual presence of the virtual character but by the action the virtual character performed (striking the ball).

One possibility to explain reduced variability in the movement kinematics is by means of spontaneous synchronization, which is a form of spontaneous pattern formation that operates according to general principles of self-organization as described by nonlinear systems. Synchronization of body movements between individuals occurs unintentionally as soon as individuals share a medium of communication (e.g., visual body information about the other person; Winfree, 2002). For instance, when performing rhythmic body movements in the presence of others, humans tend to synchronize phase and frequency of their movements with other persons without instruction to do so (Kelso, 1984; Lagarde & Kelso, 2006). Synchronization of the phase and frequency of limb movements has been observed for postural sway (Shockley, Santana, & Fowler, 2003), swinging of handheld pendulums (Schmidt et al., 1990), finger tipping (Oullier, De Guzman, Jantzen, Lagarde, & Kelso, 2008), swinging legs (Kelso, 1984), rocking chairs (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007), clapping (Neda, Ravasz, Brechet, Vicsek, & Barabasi, 2000), and when engaging in a verbal problem solving task (Richardson, Marsh, & Schmidt, 2005). Synchronization might also be able to explain the stroke variability effects. The visibility of another human should lead to larger synchronization and therefore to more consistent and less variable behavior. Therefore, if participants did synchronize their body movements to the body movements in the conditions in which the virtual player was visible, we would expect that the variance in the participants' movement kinematics decreases in these conditions. Hence, interpersonal synchronization might be one explanation for the decreased stroke variability in the conditions in which the other player's body or paddle was visible.

Our results also support the longstanding idea that action and perception are closely linked (Bootsma & Vanwieringen, 1990; Grierson et al., 2009; McBeath et al., 1995; McLeod & Dienes, 1993; Sarlegna & Blouin, 2010). Here, we can only speculate about the mechanisms which led to a coupling between visual information about the virtual player and the participant's movement kinematics and task performance. In general, different mechanisms can lead to spontaneous synchronization (see Pikovsky, Rosenblum, & Kurths, 2001, for review). In the case of human coordination, spontaneous synchronization might be the result of a link between action observation and action execution. For instance, common coding theory (Prinz, 1984; Prinz & Hommel, 2002) suggests that there is a shared representation (a common code) for both perception (e.g., seeing an action) and action (performing an action). Referring to common coding, seeing an action activates the motor representation associated with this action. Common coding is also supported by neurobiological studies which identified neurons (so-called mirror neurons) that both fire when an action is performed (e.g., grasping an object) and when the same action is observed (e.g., somebody else grasps an object; Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Iacoboni et al., 1999). The core idea behind these theories is that common coding allows an observer to understand an observed action by means of sensorimotor representations. Action understanding might allow an observer to predict the outcome of an observed action, which is regarded as important for joint action coordination (Sebanz, Bekkering, & Knoblich, 2006). Even though relatively little is known about the functional role of common coding for interpersonal coordination, a common assumption is the observation of an interaction partner guides one's own movement kinematics and thus might support synchronization.

What might be the functional role of synchronization in a task like table tennis? It has been suggested that keeping together in time and space is one of the most powerful ways to produce and reproduce communication (McNeill, 1995). Furthermore, asynchronous movements may be energetically more costly for the dyad than synchronous movements (see, e.g., Kording, Fukunaga, Hovard, Ingram, & Wolpert, 2004). In addition, Sebanz et al. (2006) suggested that a coupling between action perception and action execution has a functional role for joint action performance. They argue that joint action performance relies on humans' ability to represent and predict others' actions and to integrate predicted effects of one's own and others' actions into one's own action planning. With this hypothesis, a coupling between motor movements and visual information about the virtual player might lead to more consistent movement kinematics when the opponent is visible.

This study for the first time established a link between movement kinematics and task performance in a sensory-motor coordination task. The results showed that a nonexpert table tennis player's behavior relies on the visibility of the ball in natural conditions. However, nonexpert players are also able to use the visibility of the opponent's body and paddle to improve performance if visual information about the ball is not available. We further showed that variability of movement kinematics is affected by visual information about another person in nonexpert players. Stroke speed variability was reduced when the opponent's body or paddle was visible. Overall, our findings demonstrate that humans use visual information about the opponent in order to predict the ball trajectory and therefore support predictions in favor of current theories of joint action, that is, common coding theory, which suggest a link between action observation and execution.

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