Self-Awareness Test: How Long Does It Take Someone to Realize He/She Is Being Imitated by a Robot?

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Abstract

Humans are typically self-conscious and capable of quickly identifying when someone is imitating them. The aim of this study was to determine if humans are just as self-conscious when some*thing* (e.g. a robot) is imitating them and how synchronous the imitation must be for recognition. Using a Vicon three-dimensional motion tracking system, the position of a human subject's right arm was recorded and used to calculate joint angles. These angles were then passed to an upper body humanoid robot at a forced time delay from 6 seconds down to 0 seconds. The human subject was observed during a "dance video" and asked to fill out a survey at the completion of the video. Results showed that 80% of test subjects reported noticing the imitation an average 7 minutes into the video, while the experimenters detected an actual average of 9 minutes. The imitation was detected by the subjects with an average forced system delay of 2 seconds and a maximum of 4 seconds. Even when the robot experienced technical malfunctions, 80% of the subjects still noticed the imitation. The results confirm the hypothesis that humans are generally good at noticing they are being imitated even when the robot's motions do not match perfectly.

1. Introduction

Imitation has long been recognized as a social interaction that has reciprocal influence on both the imitator and the imitated. The general consensus in the psychology literature review is that the knowledge of one being imitated by others has a psychological effect on human subjects, especially preschool children (Meltzoff and Decety 2003). For infants, imitation helps them understand that they are similar to adults through shared behavior states. The imitation mechanism thus underlies the development of theory of mind and empathy for others. For adults, imitation reveals brain patterns for how people understand self. This has been exploited for the study of the organization and functioning of the brain. Imitation has also shown to be a particularly strong social cue that can draw and build attention with autistic children (Solis 2009).

Moreover, it is widely believed that human beings, including infants, are very good at noticing whether they are being imitated. Meltzoff tested whether 14-month-old infants can recognize if they are being imitated. His results showed that they could. Infants have been found to stare longer at the adult who was imitating them, smile more at this adult, and most interestingly, perform testing behaviors which consist of abruptly changing one's act by making sudden and unexpected movements.

These studies usually involve the interactions between a human subject and a human experimenter. Whether these results remain the same if the imitator has been a robot, not a human, is still a relatively new area of research. This study will establish the basic framework for the new research direction by determining the minimum time response of the robot (maximum time delay) to ensure that the imitation will be noticed. The study will also confirm whether human beings are indeed good at noticing that they are being imitated, even in a robot environment.

2. Methodology

A very specific setup is necessary in order to be able to test a human's reaction to robotic imitation. In particular, two main challenges exist: getting a robot to convincingly imitate the human subject, and presenting the experiment in such a way as to not bias the results with suspicion. The first challenge is merely a technical hurdle that can be systematically addressed. However, a very careful balance of deception, distraction, and consideration for the experimental environment are necessary to produce valid results.

This section will begin by discussing the implementation method, including the necessary hardware and the Matlab scripts. Then it will move on to discuss the experimental procedure, including the experimental setup and the deception methods.

Implementation

To accomplish the goal imitation for the experiment, a variety of systems needed to be combined into one cooperative unit. Motion data had to be recorded from a test subject, processed into usable position information, and converted into physical robotic behavior that the test subject could recognize. The specific implementation used was based on the availability of a 3D tracking system and an upper body humanoid robot.

Humanoid Robot Nico Nico is an upper body humanoid robot modeled after a human infant (Figure 1). Nico has a large number of degrees of freedom in his head and arms. Of greatest interest are the six degrees of freedom in his right arm and hand. In the past, Nico has been used primarily for 'Wizard of Oz' style experiments with human subjects. For this reason, the control program accepts strings of joint angles that execute sequentially. Each degree of freedom is given a separate value. Then the combined motion is executed to completion. While this permits simple control of the robot, limitations arise in the frequency at which commands can be given to the robot. In practice, two seconds between commands was the minimum time required to prevent backlog.

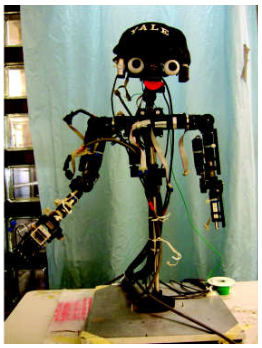

Figure 1: Nico, the upper body humanoid robot used in the study.

Vicon Motion Capture System The Vicon motion capture system is used for real-time collection of human movements. Optical motion capture uses a set of four cameras with special infrared strobe lights (Hodgins 2002). Markers made up of small spheres covered with reflective tape are placed at key locations on the body. The infrared signals reflect off the markers and are collected by the Vicon cameras. The position information of each of the markers can then be determined.

To gather sufficient information about the movement of an arm, 9 markers were used (Figure 2): the clavicle (CLAV) placed mid-chest, the corresponding location on the back (C7), the right shoulder (RSHO), the right upper arm (RUPA), the right elbow (RELB), the right forearm (RFRA), the right inner wrist (RWRA), the right outer wrist (RWRB), and the right fingers (RFIN). This set is the minimum necessary to be redundant and reliable (Vicon 2006).

Before the data can be collected in real-time, a software model must be created of the subject in a neutral position. Rigid segments corresponding to the bones in the arm are defined and connected together with joints. Special Vicon software is then able to see the markers through the cameras and distinguish which marker corresponds with which label based on the relative positions. When a given marker is visible by at least 2 cameras, its 3D coordinates become available. The full collection of all marker positions over time describes the motion of the subject.

Joint Angle Calculation In order for Nico to mimic a human subject's motions, it is necessary to convert the Vicon marker positions on the human subject to relevant joint angles. To start, the local origin and x-, y-, z-axes of the body are calculated in order to transform Vicon's global coordinates into local coordinates of the body. The origin is calculated as the midpoint of CLAV and C7. The x-axis is defined as RSHO-ORIGIN, a vector that points out to the right of the person, while the y-axis is defined as CLAV-C7, a vector that points out from the front of the person as seen in Figure 3. Finally the z-axis is defined as the cross product of x-axis and y-axis and thus it points upward.

Figure 2: The placement of the 9 markers on the right arm (note: C7 not shown)

A list of other useful vector definitions include: upperArm (RELB-RSHO), lowerArm (RWRB-RELB), ElbowAxis (cross product between lowerArm and upperArm), WristLine (RWRA-RWRB), WristCenter (midpoint of RWRA and RWRB), and hand (RFIN-WristCenter).

Six joint angles are calculated from the 9 Vicon markers: ShoulderSideUpDownAngle, ShoulderFrontBackAngle, ElbowCurlAngle, ElbowRotateAngle, WristCurlAngle, and WristRotateAngle. The curling angle of the elbow is determined from the vector formulation of the Law of Cosines, where the representative vectors are upperArm and lowerArm. The curling angle at the hand, i.e. WristCurlAngle, is similarly calculated, using vectors for the hand and the lower arm.

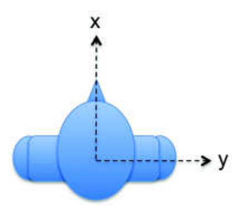

Figure 3: Top-down view of person showing head and shoulders. Z-axis is pointing out of the page.

The shoulder joint, which has three degrees of freedom, presents a slightly harder problem. The standard Euclidean rotation matrix is derived for the three rotations in succession through an angle xAngle about the current x-axis, yAngle about the rotated y-axis, zAngle about the rotated z-axis. The unit vector for the current position of the upper arm can thus be used to back-calculate the current angles of rotation of xAngle and yAngle of the shoulder joint since the pre-transformed unit vector for the upper arm is known. Likewise, the unit vector for ElbowAxis can be used to deduce zAngle since its pre-transformed unit vector is also known. Here it is important to note that although zAngle represents an angle of rotation at the shoulder for a human, is the angle of rotation at the elbow for Nico. (Wood 2007) Finally, the angle of rotation at the wrist is determined by finding the angle between ElbowAxis and WristLine. (Kadaba, Ramakrishnan, and Wootten 1990)

Time Delay With the joint angles calculated, the remaining task is to pass the proper commands to Nico at the correct time. A Matlab script was developed to store the joint angles in a buffer and mark each joint angle combination with a timestamp. A separate Matlab script then reads from the buffer. When the timestamp plus the designated delay equals the current time, the joint angle command is executed on Nico. A third script encodes the time counter and decrements the delay time at specified intervals shown in Table 1. This method allows the simple and automatic adjustment of the delay time as the experiment progresses.

Amount of Time Delay	Duration at Each Time Delay
6 seconds	1 minute
5 seconds	2 minutes
4 seconds	3 mintues
3 seconds	3 minutes
2 seconds	3 minutes
1 second	3 minutes
0 seconds	8 minutes

Table 1: The time delays throughout the 23-minute experiment.

Experiment

The experiment must occur in a controlled environment with careful attention given to what information is being communicated to the subject. Because the objective is to determine if and when a person can notice imitation, it is important the subject has no prior knowledge of the experiment and believes the experiment has a different purpose. Subjects are recruited with the explanation that they will be testing the real-time capabilities of the Vicon motion system.

Before a test subject enters the lab to begin his or her session, Nico and a commercially available interactive robotic dinosaur called "Pleo" are set to behave randomly. Upon entering the room, the subject is introduced to the three experimenters as well as the robots in the social robotics lab (Nico and Pleo). Despite Nico being the only robot of interest for the experiment, Pleo's presence prevents Nico from becoming the sole object of the subject's attention. In other words, Pleo serves as a distracting agent during the experiment. The test subject is also informed about the Vicon motion capture system.

After the subject is prepared with Vicon markers, as shown in Figure 2, he or she is instructed to watch a 23-minute "dance video" and follow the motions of the "dance

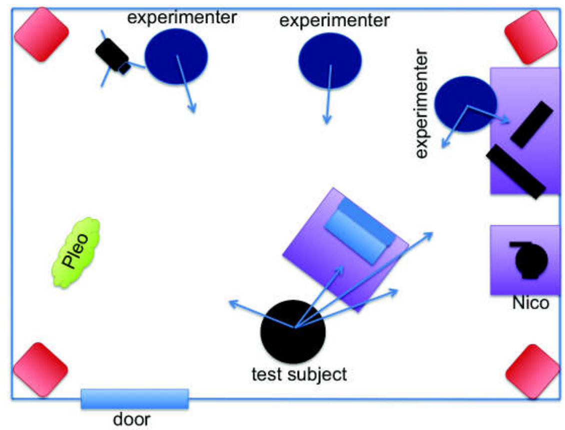

Figure 4: The physical layout of the test room. Arrows emerging from the test subject point to items of interest for the test subject during the experiment. This includes Pleo, Nico, the Vicon computer monitor, and the laptop showing the "dance video."

instructor" in the video. The video is merely a null task to ensure the subjects are tested doing the same motions. While watching the video, the subject is also asked to monitor his or her Vicon model on the computer screen and to pay attention to the environment and surroundings. If something interesting is observed, the subject is encouraged to discuss it with the experimenters. As seen in Figures 4 and 5, the layout of the room is arranged in such a way to ensure that Nico is within the peripheral vision of the subject as he or she follows the video and checks the Vicon monitor.

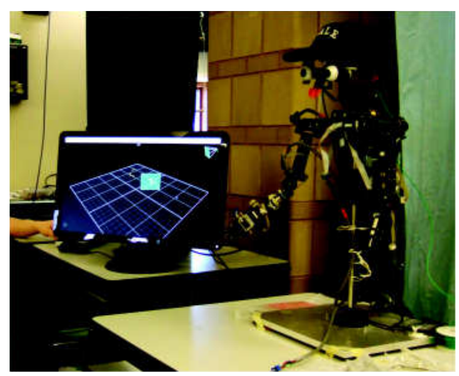

Figure 5: The peripheral view from the test subject. Test subject is clearly able to see the Vicon computer screen as well as Nico throughout the experiment.

As soon as the "dance video" starts and the subject follows the dance motions, Nico is switched from his random mode to imitation mode. (The subject is also explicitly told that the experiment begins when the dance video begins.) Initially, Nico operates with a 6 second delay behind the test subject. The delay amount is then decreased as the video continues according to the times in Table 1. Relatively little time is spent at the longer delay times of 5 and 6 seconds due to test runs indicating that not only were longer delays extremely difficult to detect, but they actually discouraged subjects from concentrating on Nico in the future.

During the experiment, the subject is being carefully observed by the three experimenters in various parts of the room. Additionally, the test subject is videotaped. Experimenters record the time that they first observe that the subject notices Nico is imitating him or her. At the end of the dance video, the subject then fills out a survey to self-report his or her own observations about the experiment.

3. Results and Analysis

Ten subjects were recruited from the academic community. Subjects were male and female, from various ethnic backgrounds and departments, as well as undergraduates, graduates, and post-doctoral candidates.

Survey results showed that all test subjects noticed Nico's arm motions while they were performing the "motion study". This implies that Nico's motions were indeed noticeable, and that the test subjects paid attention to their surroundings during the experiment. However, the subjects differed on what they thought the robot was actually doing. Based on the survey results, 60% of the subjects noticed that Nico was imitating them at some point during the experiment, while 20% thought Nico was performing random motions throughout the entire experiment. Another 10% of the subjects thought Nico was not imitating the subject's motions but rather was dancing with the music video. The remaining 10% thought Nico's every motion had been controlled by the experimenter throughout the experiment. This result confirms the hypothesis that most people are relatively good at noticing if they are being imitated, even by a robot moving only one arm.

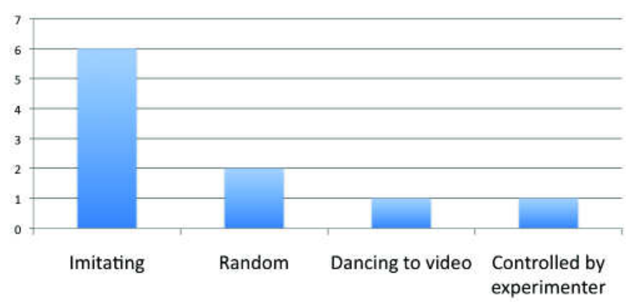

Figure 6: Histogram of subjects' overall impressions of what Nico was doing during the experiment.

When the subjects were directly asked in the survey, "Did you notice that the robot was imitating you while you were following the dance video?", 80% of the test subjects reported "yes" compared with 60% for the previous survey question. One of them previously thought Nico was dancing with the movie. The other previously thought the experimenters were controlling Nico's motions during the experiment. Even though these two subjects did not explicitly select "Imtating" in the previous survey question, they both thought that Nico had been imitating them at some point during the experiment (albeit not very well), which led them to select "yes" on the second survey question. Interestingly, one subject reported that Pleo was also imitating him.

For the 8 subjects who noticed that Nico was imitating them at some point during the experiment, they reported in the survey between 3 and 15 minutes into the dance video before realizing Nico was imitating them. The average self-reported time was 7 minutes. For 6 of these subjects, the experimenters recorded a very similar time to within +/- 2 minutes for when the subject first noticed Nico imitating them. For the remaining 2 subjects, they underestimated their time by at least 5 minutes. They likely thought they were better at noticing the imitation than how they actually performed. The actual average time, as determined by the experimenters, before the subject first noticed Nico's imitation was approximately 9 minutes. This indicates that people are generally good at remembering when they first notice they were being imitated.

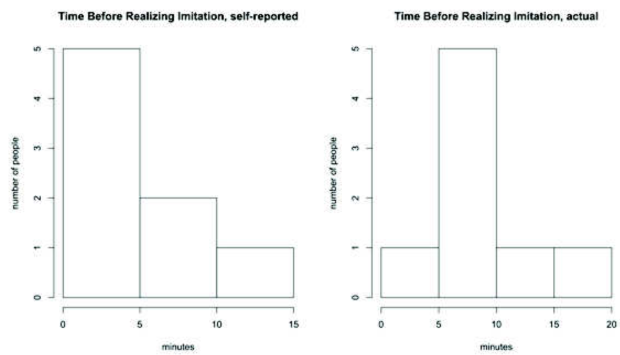

Figure 7: A comparison between the self-reported and actual times for noticing imitation.

The 9 minute average time for noticing Nico's imitations corresponds to a 2 second forced time delay. Some subjects were able to notice the imitations when the time delay was 4 seconds, while others only realized the imitations when there was no time delay.

On average, approximately 4 minutes after subjects notice that Nico is imitating them do they tell the experimenters about what they observe. This long wait before speaking up is probably due to the fact that subjects want confirm their observations before saying something that might be completely wrong. After all, the subjects were only told to take part in a "Vicon motion study."

For 4 of the test subjects, Nico's elbow joint was either "broken" or disconnected at some point during the experiment. This malfunction caused erratic behavior such as no movement or unnatural hyper-extension of the elbow. For one of the test subjects, the shoulder side up-down joint was broken. The shoulder is one of the most obvious and most utilized motions during the dance video. Even with the malfunctioning joints, 4 out of 5 of these subjects still noticed the imitations. This statistic further indicates that people are generally good at noticing that they are being imitated even when the imitations are not perfect.

It is interesting to note that there were two people who not only noticed Nico's imitations, but also a time delay in Nico's imitation. Demographic data reveals that these two test subjects are both skilled in programming, and both of them are from the mechanical engineering department. It is likely that prior programming experience, and perhaps a mechanical engineering background, heightens an individual's ability to notice more details of the robot imitation, such as time delays in the system. Being in the familiar environment of a robotics lab may encourage these subjects to consider the systems more completely. It is important to note that these subjects gave this response with no leading from the experimenters. Others may have also noticed the delay but did not explicitly state the fact.

For 30% of the test subjects, they thought that Nico was imitating them prior to the start of the experiment. This was when Nico was moving randomly. All three subjects tested their predictions but quickly realized that whatever they saw was merely a coincidence. As a result, for the first 10 minutes of the dance video, two of the three subjects dismissed the fact that Nico could possibly imitate them. Later, however, they realized that Nico was imitating them. The third subject, on the other hand, completely dismissed Nico and therefore never realized he was being imitated during the experiment.

At the completion of the survey, subjects were asked what they thought was the purpose of the experiment. Half of them listed reasonably close purposes–something to do with robots imitating human movements. One person had no hesitation believing the initial statement of purpose to "test out sensory software." Other responses were more far-fetched including the possibility that "in the future we can have a robot stand-in for stage performance in case an actor/dancer gets sick." All subjects were revealed the true purpose of the experiment after the survey.

4. Conclusion

Although 10 test subjects may not be statistically significant, numerous conclusions can still be drawn from the results. Some patterns are evident even in this small study, which may signify more general trends in the greater population.

It can be concluded that people are generally good at noticing that they are being imitated. With a delay of up to 4 seconds and malfunctioning joints, test subjects were able to identify imitation even while concentrating on a separate null task. People are also good at remembering when they notice they are being imitated. It was expected that subjects would significantly overestimate their detection time but most were within 2 minutes of their actual time.

No subjects were able to detect imitation when the time delay was greater than 4 seconds. A commonly stated statistic is that humans do not usually correlate cause and effect beyond a delay of 4 to 7 seconds and this result supported that statement. On average, the maximum time delay for someone to notice imitation was 2 seconds. It is important to note that the 2 seconds between sending commands to Nico is unrelated to the average 2-second time delay when the subject notices imitation. The former corresponds to resolution, i.e. the maximum frequency with which Nico's motors can accept commands without being backlogged. The latter corresponds to the forced time delay after the joint angles are calculated and before the joint angle commands are sent to Nico. (Recall in the experiment that, for the last 8 minutes, joint angle commands were sent to Nico every 2 seconds with no time delay and Nico thus imitated the human subject's motions in real-time.) The average time to notice imitation was 9 minutes, with an average of 4 additional minutes before reporting to the experimenters.

It was also found that humans are inherently suspicious. Even when the robot was executing random motions, some subjects thought they were being imitated and took additional steps to disprove their suspicions. Some subjects began to get slightly paranoid and think other things, such as Pleo, were also imitating them. Especially after beginning the survey, subjects began to question their surroundings in hindsight. But even with their suspicions, people were also very trusting–tell them to follow a dance video and they do. Most subjects seldom lost focus to do other things like testing the robot's motions.

In conclusion, the results of the experiment support the hypothesis that humans are capable of detecting when something, such as a robot, is imitating them, even if the imitations are delayed and the motions are not perfect. The additional conclusions reveal many more questions that could be further explored.

5. Future Improvements

A number of issues, some of them technical, were encountered during the development of the self-awareness and imitation study. Consequently, a number of things could be improved if the test were re-run in the future. For example, oftentimes the Vicon motion tracking system experienced difficulties locating the markers on a test subject, even when the test subject was standing in the middle of the room with nothing occluding the Vicon cameras' view of the markers. The issue of robustly detecting markers could be resolved by replacing existing Vicon markers with larger reflective markers, or installing additional Vicon cameras in the room (a lot more expensive option).

Another area that could be improved for the future is Nico's hardware, specifically the motors and motor controller boards. As mentioned in the Results section, during some of the experiments, Nico's elbow joint and shoulder joint malfunctioned, resulting in unnatural-looking motions or no motions at all. Additionally, the survey could have been better designed to elicit test subjects' observations and estimates of time delay in the system, including any observations of the decrementing time delay. And finally, at least 30 subjects should be tested in order for the data to yield sound statistical significance.

6. Future Work

The results of this experiment inspires further research into the area of self-awareness and imitation of humans with time delays. For example, instead of using a humanoid robot to imitate a human subject's motions with a time delay, one could use less human-like and more abstract systems such as a robotic dog or even an instrumented chain of paperclips or miniature robots to perform the imitation. (After all, one test subject thought that Pleo, who was randomly crawling on the floor, was also imitating him.) It would be interesting to see how long it takes someone to notice he or she is being imitated in this new situation.

One of the interesting observations that resulted from the experiment was that people are generally good at detecting imitation even when the imitations are not perfect. Another idea for research would be to quantify the minimum amount of realism needed in the imitation (in an anthropomorphic robot or abstract system) in order for someone to detect that he or she is being imitated.

On the other hand, if the system that is imitating the humans motions is made perfect, e.g. the Vicon system and Nico's motors are robust enough to allow perfect imitation of the test subject's arm movements, can the delay time be increased and the time to notice the imitation decreased? The current experiment started testing subjects with a 6 second time delay. At that time delay, no one was able to notice the imitation, in part because of the long time delay, but also because of imperfect imitations. Perhaps the 2-second average maximum time delay could be increased if the imitations were made more real.

It is possible that this maximum delay time could be further increased if there were visual cues that guided the subject into noticing the imitations. For example, if Nico looked at the test subject while he or she performed a motion, and turned to look at his own arm and then performed the same arm motion, would the test subject immediately notice, even if there was a significant time delay ($>$10 seconds) between Nico's movements and the subject's movements?

And finally, it would be interesting to find a correlation between personality types and the time it takes someone to notice he or she is being imitated. During the present experiment, it was noticed that very sociable test subjects tended to notice Nico's imitations much faster than very quiet and shy test subjects. Although this was only anecdotal observations – no personality data was captured in the survey – time to notice the imitation may be correlated with personality type.

The present research project has opened up many avenues in which to explore human reactions to imitations. The four ideas mentioned above are by no means exhaustive.

7. Acknowledgments

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