An adaptive robot teacher boosts a human partner's learning performance in joint action

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Abstract— One important challenge for roboticists in the coming years will be to design robots to teach humans new skills or to lead humans in activities which require sustained motivation (e.g. physiotherapy, skills training). In the current study, we tested the hypothesis that if a robot teacher invests physical effort in adapting to a human learner in a context in which the robot is teaching the human a new skill, this would facilitate the human's learning. We also hypothesized that the robot teacher's effortful adaptation would lead the human learner to experience greater rapport in the interaction. To this end, we devised a scenario in which the iCub and a human participant alternated in teaching each other new skills. In the *high effort* condition, the iCub slowed down his movements when repeating a demonstration for the human learner, whereas in the *low effort* condition he sped the movements up when repeating the demonstration. The results indicate that participants indeed learned more effectively when the iCub adapted its demonstrations, and that the iCub's apparently effortful adaptation led participants to experience him as more helpful.

I. INTRODUCTION

As robots become increasingly prevalent in many domains of everyday life, such as disaster relief, health care, education, and manufacturing ([1], [2], [3], [4], [5]), researchers are devoting ever more attention to developing new ways of optimizing human-robot-interaction. One challenge in this regard is to mitigate the risk of human interactants becoming frustrated or impatient when an interaction with a robot does not go well (for example because their robot partner makes mistakes or is slow in making its contribution), and subsequently avoiding interactions with robots in general. This risk may be particularly acute insofar as many of the people who will be asked or expected to interact intensively with robots may not have a high degree of prior familiarity with robots or with technology in general (e.g. senior citizens).

This is especially important for designing robots to teach humans new skills or to lead humans in activities which require sustained motivation (e.g. physiotherapy, skills training). Robot teachers, much like human teachers, will need to ensure that their learners sustain motivation so that they learn effectively and get the most out of the interaction.

A. Related Research

To address this challenge, Powell and Michael ([6]; cf. also [7]) have recently proposed that a potentially effective and low-cost strategy could be to develop design features that serve to maintain a human's sense of commitment to an interaction with a robot. For example, in the context of human-human interaction, it has been hypothesized [8] that the perception of a partner's effort increases people's sense of commitment to joint actions, leading them to reciprocate by investing more effort and attention in the joint action as well. The rationale for this is that a partner's investment of effort indicates that the joint action is valuable to them - i.e. that they are willing to invest physical and/or cognitive resources in order to perform the activity well with that partner. Indeed, if we understand effort as - '... the process that mediates between how well an organism can potentially perform on some task and how well they actually perform on that task' [9], then an agent's investment of effort in a joint action is a direct indication that they are willing to sacrifice resources in order to perform that joint action well with their partner. If so, they are likely to be happy if the joint action goes well and disappointed if it does not (especially given that they have invested effort). As a result, in response to the perception of a partner's effort, people may increase their own investment of effort in a joint action as a useful means of maintaining a good rapport as well as a good reputation. In the context of human-human interaction, several studies provide support for this general hypothesis i.e., that the perception of a partner's effort elicits a sense of commitment, leading to increased effort, persistence and performance on boring and effortful tasks ([10], [11], [12]). Building on this, in [13] the authors have recently found evidence that the perception of a robot partner's apparent investment of cognitive effort boosted people's persistence on a boring task which they performed together with a robot.

One specific form of effort investment which may be particularly relevant in the context of human-robot interaction is the adaptation of kinematics to facilitate action intelligibility. Research on the adaptation of kinematics takes its starting point in previous work on so-called 'motionese' [14]. This term refers to the style of movement which caregivers tend to spontaneously adopt when demonstrating things to infants - i.e., slowing down their movements, introducing more segmentation, and standing in closer proximity to infants when demonstrating actions than when they demonstrate actions for adult observers [14]. In the context of human-robot interaction, Vollmer et al. [15] found that human

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participants produce motionese in demonstrations directed towards a robot learner, and Nagai and Rohlfing [18] showed that a robot observer could be designed to pick up on, and extract information from, motionese produced by a human. Moreover, Chandra et al. [16] showed that the interaction with an adaptive robot enabled children not only to teach but also to improve their own learning of letters.

B. The Current Study

Building upon these previous findings, we hypothesized that if a robot invests physical effort in adapting its kinematics to a human partner in a context in which the robot is teaching the human a new skill, the human partner will perceive this as indicating the robot's commitment to the teaching task. We also hypothesized that the robot's effortful adaptation to the human would facilitate the human's learning, and lead to an increase in the level of rapport experienced by participants. Specifically, we tested these hypotheses in a scenario in which the humanoid robot iCub ([17], [18]) and a human participant alternated in teaching each other new skills. In the experiment, the robot demonstrated movement sequences to a human with either a high or a low level of effort (in separate experimental conditions), thus manipulating its apparent commitment to the teaching task.

II. METHODS

A. Experimental Design

We designed a task consisting of two distinct phases. In the first (the *robot teaching phase*), participants were required to learn a sequence of movements taught by the robot (see the experimental setup in Figure 1). In the second phase (*participant teaching phase*), participants taught the robot words by drawing them in the air. The experimental manipulation was implemented in the robot teaching phase. Specifically, we manipulated the robot's commitment to teaching by varying its level of effort when demonstrating the movement sequences: *high effort* condition versus *low effort* condition. In both conditions, the robot first demonstrated the movement sequence with a baseline speed. If the participant asked the robot to repeat the sequence, however, the robot repeated it more slowly in the *high effort* condition, or more quickly in the *low effort* condition. These two conditions were presented in separate counterbalanced test blocks in a within-subjects design.

The robot was iCub ([17], [18]), a humanoid robot developed as part of the EU project RobotCub. It is approximately 1m tall with the appearance of a child.

B. Procedure

Prior to the experiment, there was a baseline *participant teaching phase* in which the participant drew a word first in front of the robot and then in front of the human experimenter. Next, there was a familiarisation phase, in which the participant was left alone to become familiar with the robot and with the procedure for the *robot teaching phase* and the *participant teaching phase*. To this end, the robot first demonstrated individual movements and then a short sequence of 3 movements, and the participant was then instructed to teach individual letters and then a short word of 3 letters.

Participants were then informed that the robot would have two different teaching strategies in the two sessions (i.e. experimental blocks) of the experiment, but no specific details about these strategies were revealed. Participants were also asked to complete various questionnaires (see below).

The core of the experiment consisted of two (counterbalanced) blocks with six trials each. Each trial consisted of a *robot teaching phase* followed by a *participant teaching phase*.

During the *robot teaching phase* of each trial, the iCub demonstrated one sequence of movements which the participant was required to observe, memorize and repeat. After the robot's demonstration, the participant was required to reproduce the sequence in the correct order. For each sequence, the participant was given two chances to perform the movement sequence correctly (meaning that if the participant did not understand the sequence the first time, the robot demonstrated it a second time). In the *participant teaching phase* of each trial, the participant was instructed to teach the iCub a word (which was displayed on the screen behind the robot) by drawing it in the air with their right hand. If the iCub did not understand the word the first time, participants were required to repeat the demonstration. In order to simplify data segmentation, participants were asked to press a key on the keyboard (placed between them and the robot) before starting and when ending drawing.

For each experimental block, the robot provided positive feedback for one word after the participant's first demonstration, indicating that it had understood the word after the first demonstration. For the other five words, the robot asked for a second demonstration. After the second demonstration, the robot always told the participants that it had understood better. The experimenter was hidden in 'Wizard of Oz' fashion [19] in order to create the impression that the robot was not controlled by anyone - although the experimenter's intervention was needed to start the interaction and in order to determine whether the participant had repeated the sequence correctly.

After the experiment, the same questionnaires that participants had completed prior to the experiment were again administered in order to measure any changes in participants' perception of the robot.

C. Setup and technical implementation

We leveraged the iCub middleware YARP (Yet Another Robot Platform [20]) to build a distributed system of several computers connected to the robot network. The computers in the network were connected to other devices: 1) a computer keyboard connected via USB from which participant's could begin each trial, 2) a television monitor behind the iCub connected via HDMI displaying the words participants were to teach the iCub, 3) a RGB-D camera through USB through which the experimenter could monitor participant's activities

to assess whether they performed their movement sequences correctly. The iCub's behaviour (specifically the movements and the speech) and words' appearance on the screen were both controlled by a main YARP module while kinematic data collection was synchronized and controlled by the participant's presses of a button on the keyboard.

The main module consisted of a finite-state machine where the trials of teaching the word and the sequence followed one another.

During the *participant teaching phase*, the transition from one state to another was triggered by the participant's key press. Specifically, upon the first key press in a given trial, the displayed word would disappear. Upon the second key press (after the participant had finished drawing the word) the robot provided feedback, telling them whether it had understood or not.

During the robot's teaching task, the transition from one state to another was triggered by the experimenter's key press. After the robot had demonstrated the sequence and the participant had tried to reproduce it, the experimenter (who was observing the scene through the robot camera eye), pressed the "Y" key if the sequence was correct or "N" key if the sequence was incorrect. This triggered positive or negative feedback from the robot (this was repeated for two times if the sequence was not correct and the robot has to do a second repetition).

III. ROBOT STIMULI

For the robot's teaching task, the movements of the sequences were pre recorded in order to ensure that participants were presented with exactly the same movements with the same timing. The robot's movements were generated by the Constant Time Position Service (CTP Service), which takes the required position in joint space and movement timing as input. We created a library of 22 upper body movements (combining torso, arm, and head movements) and randomly combined these to generate twelve sequences of five movements (see some examples of movements in Figure 1). We also ensured that for each sequence at least one movement was new and never seen by the participant, so that they never became too familiar with the robot's movements. The movements were also designed such as not to have any meaning. That is, we excluded movements like 'waving hello' or 'giving thumbs up'. This was in order to make it difficult for participants to leverage their semantic memory to remember the sequences instead of memorising the movements. An overly simple task would have meant that participants would never have to ask the iCub to repeat the sequence thus rendering the change in effort/commitment to the task superfluous.

In both conditions, the robot demonstrated the sequences with a duration T_i for each movement i for the first demonstration, and then for the second demonstration with a duration of $0.75T_i$ for the *low effort* condition, or with a duration of $1.39T_i$ for the *high effort* condition. For instance, if a sequence was ~15 seconds in the first repetition (so with the baseline speed), in the second repetition it would become ~11 seconds in the *low effort* condition and ~21 seconds in the *high effort* condition. These values were selected after pilot testing (with ten participants) where we saw experimentally that the increase/decrease in speed could be noticeable and at the same time safe for being performed from the robot (especially in the low effort condition with faster movements). The baseline speed was designed in order to make it very difficult for participants to understand the sequence after the first demonstration. This was done to maximise the number of times participants would appreciate the robot's change of speed in the two experimental blocks.

After each movement, the robot returned to the home position at the same speed, but the movements were less segmented in the *low effort* condition than in the *high effort* condition. To make the interaction more naturalistic, we activated the robot's face detector module to make it look at the participant during the experiment, as well as the blinking and the 'breathing' (a set of slight movements of the arms to give an impression of vitality) when the robot was idle.

A. Participants

We recruited 21 participants (mean age 33 years ± 13 SD). 11 participants were female, 10 male. The regional ethics committee approved the protocol and all participants gave informed consent before participating, and were fully debriefed after the experiment.

B. Data

During the experiment we administered questionnaires and took video recordings of the participants through the RGB-D camera for 21 participants. 11 participants were presented with the *low effort* condition and then the *high effort* condition, 10 participants were presented with the opposite order. Participants were asked to answer the following questions:

- "What differences do you think there were in the teaching strategy of the robot in the two sessions [experimental blocks]?" (open question, at the end of the experiment)
- "Did you have the impression that iCub helped you when you had difficulties in repeating the sequence of movements?" (on a scale from 0 to 5, after the two blocks).

Additionally we also asked to indicate how close they felt towards the iCub using the Inclusion of Other in the Self (IOS) Scale [21] from 1 to 7, before the experiment and after the two blocks.

In order to evaluate participants' performance, the videos were viewed by the experimenter, who scored each trial according to how many movements were reproduced correctly in the correct sequence. Performance was calculated as the number of correct movements divided by the total number of movements presented (5). This was done separately for the first repetition (i.e., after the first demonstration from the iCub) and the second repetition (i.e., after the second demonstration from the iCub).
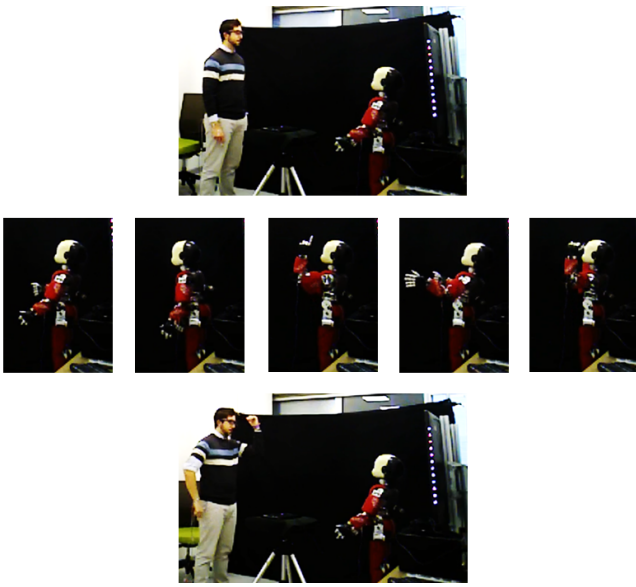
Fig. 1. Setup and robot's home position (above), an example of a sequence of five movements (center) and participant trying to repeat the sequence (below) during the *robot teaching phase*.
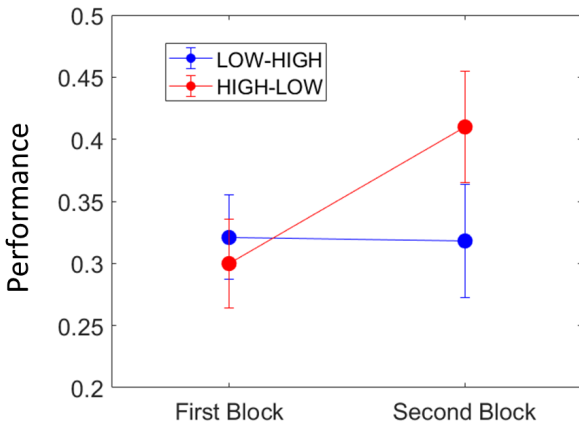

Fig. 2. Performance of the subjects after the first demonstration of iCub.
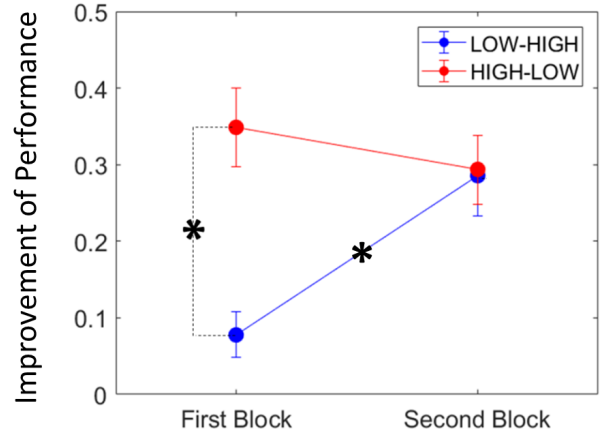

Fig. 3. Improvement in performance from the first to the second repetition in the two experimental blocks for participants who had the low effort condition first and then the high effort condition (blue), and for participants who had the other order (red).
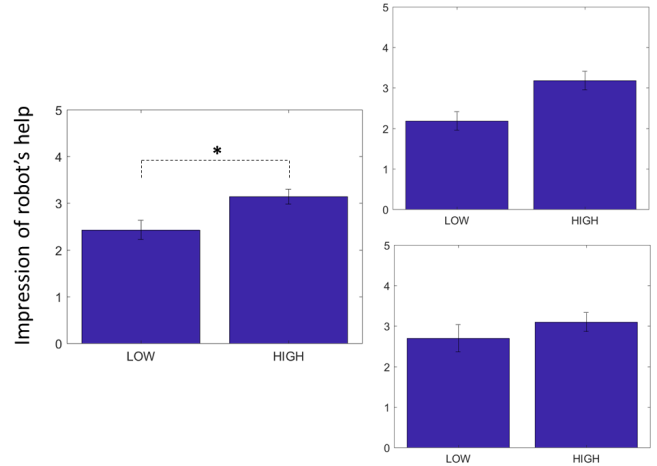

Fig. 4. Participants' impression that iCub helped them when they had difficulty in repeating (from 0 to 5), for all the subjects (above), for participants who had the LOW-HIGH order (bottom, left) and the HIGH-LOW order (bottom, right).

IV. RESULTS

The aim of this study was to investigate whether it is possible for a robot teacher to convey different levels of commitment by changing its kinematic effort, and whether this would facilitate human participants' learning task. To do that, we compared participants' performances between the two conditions and analyzed their responses to the questionnaires.

A. Performance

Participants found the sequences equally difficult in the two sessions, as demonstrated in Figure 2 which shows that participants' performance after the first robot demonstration did not differ between the two test blocks - i.e. neither for participants exposed first to the *low effort* condition

and then to the *high effort* condition (LOW-HIGH) (in the first block, M=0.32, SD=0.14; in the second block M=0.32, SD=0.19), nor for participants exposed first to the *high effort* condition and then to the *low effort* condition (HIGH-LOW) (in the first block, M=0.30, SD=0.15; in the second block, M=0.41, SD=0.19). Indeed, a two-way Mixed Model Anova on the performance after the first repetition with "block" (First block or Second block) as repeated-measures factor and "blocks order" (LOW-HIGH or HIGH-LOW) as between-groups factor, did not find any significant difference neither between the blocks (F(1,19)=1.64, p=0.203), between the orders (F(1,19)=0.31, p=0.583), nor was the interaction between the two factors significant (F(1,19)=1.94, p=0.179).

Participants showed a significant improvement in performance after the second robot demonstration relative to its
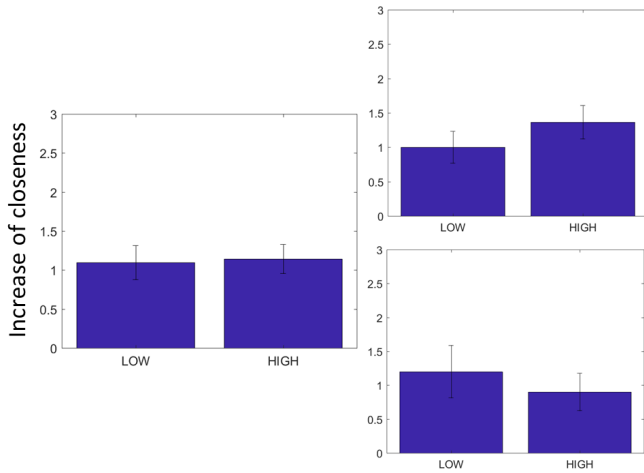
Fig. 5. Difference in closeness towards the robot between the answer after the two conditions (LOW, HIGH) and the answer given before the experiment, for all the subjects (above), for subjects that had LOW-HIGH order (bottom, left) and HIGH-LOW order (bottom, right).

first demonstration (performance after the second repetition - performance after the first repetition) - see Figure 3.

A two-way analysis of variance on the improvement in performance shows that there was no main effect of block (F(1,19)=2.87, p=0.107), and no order effect (F(1,19)=3.80, p=0.06). However, the interaction between block number and block order was significant (F(1,19)=8.56, p=0.009). A Bonferroni post-hoc test (p=0.019) indicated that: in the first block, participants in the *high effort* condition improved significantly more (M=0.35, SD=0.22) than participants in the *low effort* condition (M=0.08, SD=0.13). This demonstrates that a higher effort investment on the part of the robot enabled participants to better memorize the sequence, and thus improved their performance. Moreover, participants who only showed a small improvement between the first and second demonstration in the first block (LOW-HIGH, blue in Figure 3) exhibited a significantly higher improvement in the second block (one-tailed Bonferroni post-hoc, p=0.048). No other comparisons reached significance, indicating that in the second block, all participants displayed a significant improvement in performance, regardless of condition.

This can be due to the fact that during the second block, independently of how much effort the robot invested, participants had had considerable practice with the routine and became proficient at adjusting their movements in response to the second demonstration of each sequence. Conversely, during the first block, the robot's effort made a large difference in terms of improvement of performance, as participants who were in the *high effort* condition exhibited a significantly higher improvement.

B. Questionnaires

In the questionnaire after the experiment, we asked participants which differences they thought there were in the teaching strategy of the robot in the two sessions. This was an open question, so the answers were quite different from one

participant to the next. Despite the fact that the experimenter explicitly said at the beginning of the experiment that there would be two different robot teaching strategies in the two sessions, 33% (7) of participants replied that there was no difference between the two sessions. 57% (12) of participants noticed a difference in the speed, and among them 6 said that the difference was in the speed of the second repetition (which was indeed the modification we applied), 1 in the segmentation (the other modification we applied), 5 in speed in general. 10% (2) of participants replied that there was a difference in the difficulty. Other differences that were observed partained to symmetry and to torsion movements.

Although not all participants were able to identify what had changed in the robot's behavior between the two sessions, the change had an impact on their perception of the robot.

Figure 4 displays the answers given by participants when asked to answer the question about whether they had the impression that iCub helped them when they had difficulties in repeating the sequence of movements (on a scale from 0 to 5). A Mixed Model ANOVA with Effort (two-levels: High - Low) as within factor and Block Order (two-levels: HIGH-LOW, LOW-HIGH) as between factor yielded a main effect for the effort (F(1,19)=9.56, p=0.006), such that the average answer value was significantly higher for the *high effort* (M=3.14, SD=0.17) than for the *low effort* (M=2.44, SD=0.17). In contrast, the blocks' order effect (F(1,19)=0.59, p=0.452) was not significant, nor was the interaction (F(1,19)=1.76, p=0.201). Therefore, independently of block order, participants had a greater impression that the robot had helped in the *high effort* condition.

Participants were also asked to indicate how close they felt towards the iCub using the IOS Scale from 1 to 7, before the experiment and after the two blocks. We computed the difference between one block and the baseline (the answer given before the experiment) (Figure 5). A *t*-test comparing increment in closeness between LOW and HIGH individuates a significant difference only for the LOW-HIGH order (p=0.038), although this test does not resist Bonferroni correction. A Mixed Model ANOVA shows that neither effort (F(1,19)=0.06, p=0.808) nor the block order (F(1,19)=0.12, p=0.737) were significant, but there was a significant interaction (F(1,19)=6.60, p=0.019).

V. DISCUSSION

The current study examined human-robot interaction in a scenario in which the iCub and a human participant alternated in teaching each other new skills. Specifically, we probed whether the iCub's effortful adaptation to the human would facilitate the human's learning, whether the human partner would perceive the iCub's effortful adaptation as indicating a commitment to the teaching task, and whether the effortful adaptation would generate rapport.

The results indicate that participants' performance increased more from the first to the second demonstration of a sequence in the *high effort* condition than in the *low effort* condition. In other words, participants learned better

when the iCub slowed down his demonstration and increased segmentation in between movements. The results from the questionnaires also indicate that participants experienced the robot as more helpful in the *high effort* condition, and that those participants who experienced the *low effort* condition followed by the *high effort* condition felt closer to the robot during the *high effort* condition.

Our findings build upon a recent body of research investigating how movement kinematics can be adapted to increase legibility to observers in the context of HRI. Indeed, the potential to make robots' movements more easily legible to human interactants is a crucial goal of current and future research in social robotics [22]. Moreover, our findings also contribute to research highlighting the important role of motion in communicating implicit messages and in intuitive communication in general ([23], [24]). In this respect, the current study takes a step further by tapping into the concept of a sense of commitment [12], which may offer considerable potential in the context of social robotics. Indeed, Székely et al. (forthcoming) have already shown that by eliciting human interactants' sense of commitment to an interaction with a robot, their persistence and patience can be enhanced. This has important implications insofar as it highlights the possibility that the adaptation of movement kinematics may be used not only to increase legibility but also to enhance human interactants' persistence, effort and patience within human-robot interactions.

Our findings also build upon research in developmental psychology which has been identified as harboring considerable potential for social robotics. Specifically, a wealth of research has shown that human infants benefit from the spontaneous use of motionese on the part of caregivers – i.e., caregivers slow down their movements, introduce more segmentation, and stand in closer proximity to infants when demonstrating actions than when they demonstrate actions for adult observers [14]. Our findings also build upon previous efforts to implement motionese in the context of human-robot interaction. Vollmer et al. [15] found that human participants produce motionese in demonstrations directed towards a robot learner, and Nagai and Rohlfing [25] showed that a robot observer could be designed to pick up on, and extract information from, motionese produced by a human. Our findings extend this previous research by showing that a robot can implement motionese in teaching motion sequences to a human, and that this benefits human learners.

It would be valuable for future research to investigate other contexts in which robot motionese may facilitate human learning, such as in producing or using novel tools or machines. It would also be important to investigate to what extent the skills or information learned with the help of robot motionese are recalled after several weeks or months – in other words, to probe whether robot motionese also facilitates the automatization of new skills or the encoding of new information in long-term memory.

In teaching more complex action sequences, it is often effect for a teacher to break up longer sequences into shorter components, and to *scaffold* learning by focusing on each of the components sequentially, and identifying which of these components learners need extra help with. A system that could evaluate the performance of an end-user in real time and tailor its motionese to the specific learning needs of that end user could be particularly useful for real-life teaching scenarios.

The potential to use movement kinematics not only to optimize teaching in HRI but also to generate and maintain a sense of commitment has important implications in such contexts as physiotherapy, exercise classes, or other skill training programs. In particular, if movement kinematics can be used an effective and inexpensive strategy for boosting human learning from robots and for building up a sense of commitment to the interaction, then humans may not only find it easier to learn, but may also be more motivated to do so.

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