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Physiological and subjective evaluation of a human–robot object hand-over task

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A B S T R A C T

In the context of task sharing between a robot companion and its human partners, the notions of safe and compliant hardware are not enough. It is necessary to guarantee ergonomic robot motions. Therefore, we have developed Human Aware Manipulation Planner (Sisbot et al., 2010), a motion planner specifically designed for human–robot object transfer by explicitly taking into account the legibility, the safety and the physical comfort of robot motions. The main objective of this research was to define precise subjective metrics to assess our planner when a human interacts with a robot in an object hand-over task. A second objective was to obtain quantitative data to evaluate the effect of this interaction. Given the short duration, the “relative ease” of the object hand-over task and its qualitative component, classical behavioral measures based on accuracy or reaction time were unsuitable to compare our gestures. In this perspective, we selected three measurements based on the galvanic skin conductance response, the deltoid muscle activity and the ocular activity. To test our assumptions and validate our planner, an experimental set-up involving Jido, a mobile manipulator robot, and a seated human was proposed. For the purpose of the experiment, we have defined three motions that combine different levels of legibility, safety and physical comfort values. After each robot gesture the participants were asked to rate them on a three dimensional subjective scale. It has appeared that the subjective data were in favor of our reference motion. Eventually the three motions elicited different physiological and ocular responses that could be used to partially discriminate them.

1. Introduction

Human–Robot Interaction (HRI) is getting more and more attention since the barrier between humans and robots begin to fade. The design of the interaction becomes a major challenge when the robot and the humans coexist in the same environment and cooperate to achieve tasks together. Besides the safety and the comfort of the interaction, an important property that is often ignored in the literature is the distribution of the cognitive load in the interaction. In an “object hand over” task, often it is the human who decides where the interaction will happen and adapts himself/herself to the motions of the robot. Even though this behavior allows the human to manage the interaction, it also puts he or she in charge of managing the behavior of the robot, thus increasing his or her cognitive load and reducing the intuitiveness of the interaction. Therefore, we have developed Human Aware Manipulation Planner (Sisbot et al., 2008, 2010; Marin et al., 2008), a motion planner

specifically designed for human–robot object transfer tasks. The novelty of this planner is that it takes explicitly into account the human. In particular, our planner computes a path towards a robot posture considering a number of criteria that are extracted from user studies (Koay et al., 2007; Dautenhahn et al., 2006) and from the proxemics theory (Hall, 1966). A first criterion is the legibility of the interaction as the object transfer must be as visible and predictable as possible. A second criterion is the safety of the interaction as the robot must stay as sufficiently far as possible and transfer the object in the safest way. A third and last criterion is the physical comfort of the interaction as the object has to be carried to a place where the human should not make too much effort to reach and grasp it. Indeed, the planner computes automatically the best position where the robot-to-human object transfer should take place by reasoning on human’s kinematic structure, field of view and preferences. It then computes the path to reach this position and synthesizes motor commands to execute the motion. Eventually our planner decides the moment when the robot-to-human object transfer should happen and when to release and retract.

Therefore, it becomes obvious that there is a need to design appropriate metrics for the tuning and the optimization of such criteria.

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Various methods are used to assess HRI from qualitative and quantitative points of view. They aim at better understanding and improving the design of this interaction in terms of social acceptance, cognitive and emotional impacts. Classical user studies consist of measuring the participants' performance regarding the number of errors, the occurrence of conflicts (Dehais et al., 2009), reaction time and task completion rate: these metrics have to be tuned and adapted (Steinfeld et al., 2006) regarding the task (e.g. teleoperation, supervision...). Nevertheless, given the short duration, the relative ease and the qualitative aspect of our "object hand over" task, such classical quantitative measures based on accuracy or reaction time are unsuitable to compare the gestures. A more suited method is to obtain subjective data by submitting a survey or a questionnaire when interacting with a robot. A specific type of questionnaire consists of self-rated scales that give multidimensional subjective inputs such as mental or physical effort, pleasantness, level of anxiety (...) induced by the interaction. This method offers both qualitative and statistical data as shown by Kanda et al. (2004) study where robot "eye" contacts and well synchronized humanoid motions were positively correlated with positive subjective evaluation. This is particularly true in two studies (Hayashi et al., 2007; Shiomi et al., 2007) respectively conducted in a train station and a museum: the large sample of analyzed questionnaires combined with some of the pre-cited metrics, has led the authors to assess with statistical evidences the ability of the robots to attract attention and to help or inform the user. Since numerous self-rated scales exist, Bartneck et al. (2009) have recently proposed a standardization of five HRI key concepts: anthropomorphism, animacy, likeability, perceived intelligence and perceived safety. Although this approach is interesting, it may be too generic and it does not take into account some cognitive aspects (e.g. predictability of the robot actions...) or some "physical" aspects of the interaction such as the physical comfort. Eventually if the subjective self-reports are convenient and easy to use, their validity remains quite limited: the participants' answers may be influenced by a *posteriori* rationalization, their state of mind, and the desire to satisfy the researcher's implicit objectives (Bethel et al., 2007; Mandryk et al., 2006).

Therefore, a number of authors (Koay et al., 2007; Bartneck et al., 2009) propose to assess the robot gestures with complementary physiological data in order to provide cues both on the cognitive activity and on the emotional states (Causse et al., 2009; Granholm and Steinhauer, 2004; Collet et al., 2009). Indeed there is a growing interest in HRI to derive the user anxiety and stress from heart rate (Rani et al., 2002), blood pressure (Housman et al., 2007), electroencephalography (EEG) (Wada et al., 2005; Wilson and Russell, 2002), skin conductance response (Takahashi et al., 2001; Munekata et al., 2006), urinary tests (Wada and Shibata, 2006), pupillary dilation (Yamada et al., 1999), respiratory rate and respiratory amplitude and muscular activity (Itoh et al., 2006). An interesting approach consists of collecting both these latter objective data and subjective ratings (Nonaka et al., 2004). Probably one of the most convincing studies in HRI has been conducted by Kulic and Croft (2007) since the experimentation has been realized with a real manipulator arm and a large number of subjects ($n = 36$). The participants' responses to different robot motions were collected using a 5 points Likert subjective scale and three physiological sensors (myogram activity on the eye brow, electrocardiogram, and skin conductance). Although the subjects were passive as they did not interact with the robotic arm, they have reported less anxiety, felt calmer with the safe robot motion, and showed significantly lower skin conductance value. On the contrary, fast motion has elicited strong physiological responses. Whereas most of the physiological studies in HRI are focused on the assessment of the emotional state of the user, very few have considered the physical comfort, such as the muscular effort (West et al., 1995) induced

by the interaction. Moreover, most of these research using electromyograms (EMG) are biofeedback or neuromuscular assistance oriented (Merletti and Parker, 2004). Eventually, to the author knowledge, no studies have derived behavioral data from eye-tracking techniques despite visual perception is essential to interact with robots (Kulić, 2005).

A limited number of studies in HRI have explored human interacting directly with a physical humanoid or mobile robot (Bethel et al., 2007), and in this perspective we have developed Jido, a real "pick-and-place" robot. For the purpose of the experiment a reference motion, which entirely suits *a priori* adequate legibility, safety and comfort criteria, has been integrated to our planner. In addition, two other robot motions, combining different levels of legibility, safety and physical comfort values, were conceived to compare them with the reference motion. The first objective of this study was to rate our reference gesture from the other ones using self-reports of legibility, safety and physical comfort. The second objective was to assess the effects of the three gestures on the participant's galvanic skin conductance response, the deltoid activity and ocular activity. Considering that the interactions with the robot were quite short, the galvanic skin conductance response was chosen as the skin phasic response is highly dynamic with short response latencies (Kulić and Croft, 2007; Rani et al., 2002). The deltoid activity measurement was selected as this muscle starts the forward raising of the arm when the participant interacts with the robot. Eventually the eye movements were recorded using an eye tracker as this technique is a relevant indicator of task complexity (Wilson and Eggemeier, 1991).

2. Materials and methods

2.1. Participants

Healthy volunteers ($n = 12$) were recruited by local advertisement. Inclusion criteria were: young (mean age: 26.5 ± 5.35) male ($n = 10$) and female ($n = 2$), right-handed, postgraduate (mean years of education: 19 ± 2.15). Non-inclusion criteria were sensory deficits, neurological, psychiatric or emotional disorders and/or being under the influence of any substance capable of affecting the central nervous system. No grants were offered to the volunteers for their participation to the experiment. The participants gave their informed consent after having received complete information about the nature of the experiment.

2.2. Experimental set-up

The experiment took place in a vast empty room with human oriented toward the robot and the wall to avoid any possible disturbances that might occur during the study. The experimental set-up was composed of Jido (Fig. 1), an MP-L655 platform from Neobotix, equipped with a 6°-of-freedom Mitsubishi PA-10 arm. Several sensors were available on the platform: sonars, two laser range finders, two stereo camera banks (one mounted on the arm and the other on a pan-tilt unit on the base platform), several contact sensors and a wrist force sensor. The Human Aware Manipulation Planner is integrated to Jido robotic platform in LAAS/CNRS.

2.3. Motions' descriptions

The participants were subjected to three different types of object hand-over robot motions. The motions were separated by their speed (also by the acceleration and jerk), their shape and the moment to release the object.

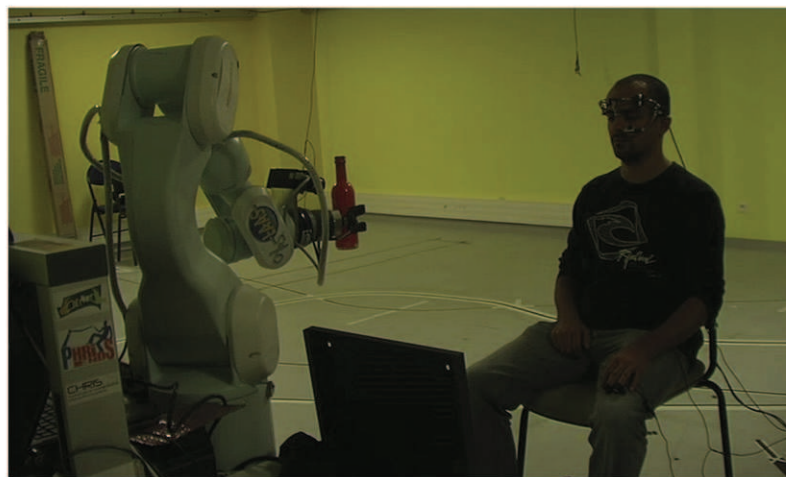
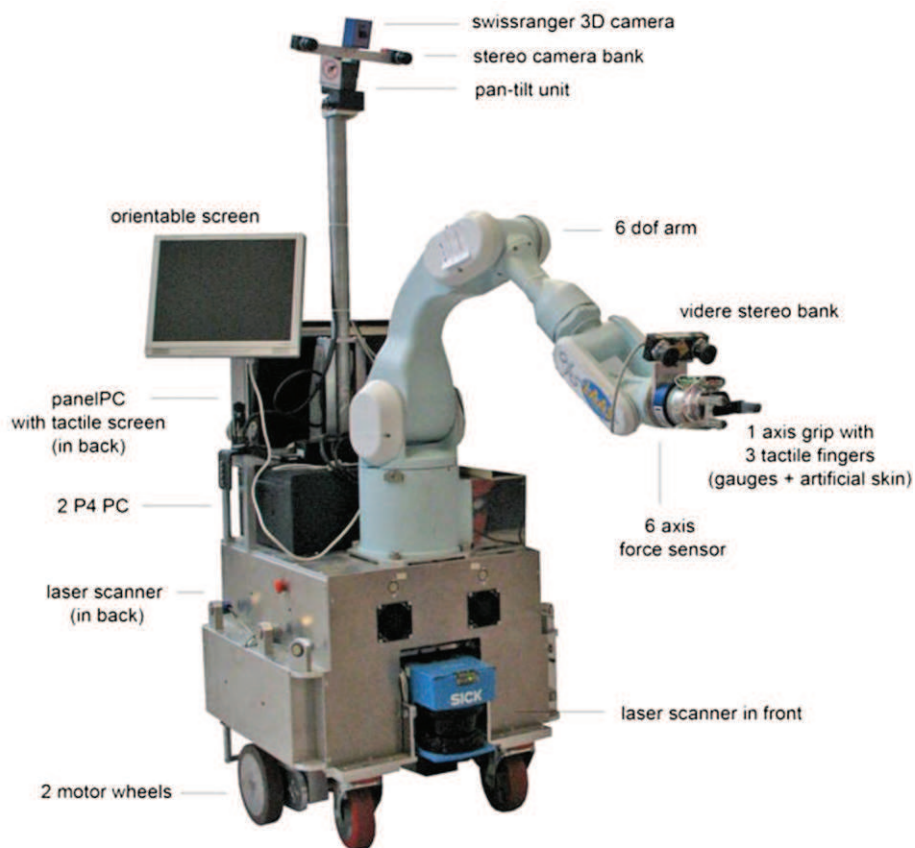


Fig. 1. Jido and a view from the experimental setup. The human is placed in front of the robot on a chair.

The robot was correctly placed toward the human. Yet human contribution was introduced with the use of Detect-Human-Grasp function which gives the robot the ability to release the object when the human grasps it.

2.3.1. Motions generation

The motions of the robot that we use in this experiment are generated by Human-Aware Motion Planner (Sisbot et al., 2007, 2010). This planner takes into account the safety, the field of view, the posture and the kinematics of the human in order to generate safe and comfortable robot paths. Three interaction criteria are incorporated into the planner: legibility, safety and physical comfort. These criteria are modeled as 3D cost functions

mapped around the human. The cost map generated by the cost functions are illustrated in Fig. 2. The legibility criterion is modeled by a cost function representing the effort required by the human head and body to see a point in the environment. The safety cost function is a decreasing function depending on the distance between the human and a position. The physical comfort criterion takes into account the human's kinematic to compute a physical comfort cost mapped around the human. The comfort cost of a point is calculated by merging the human arm joint displacement and the arm's potential energy to reach that point. To find the object hand-over position, we search the minimum cost point that minimizes the weighted combination of these 3 cost functions.

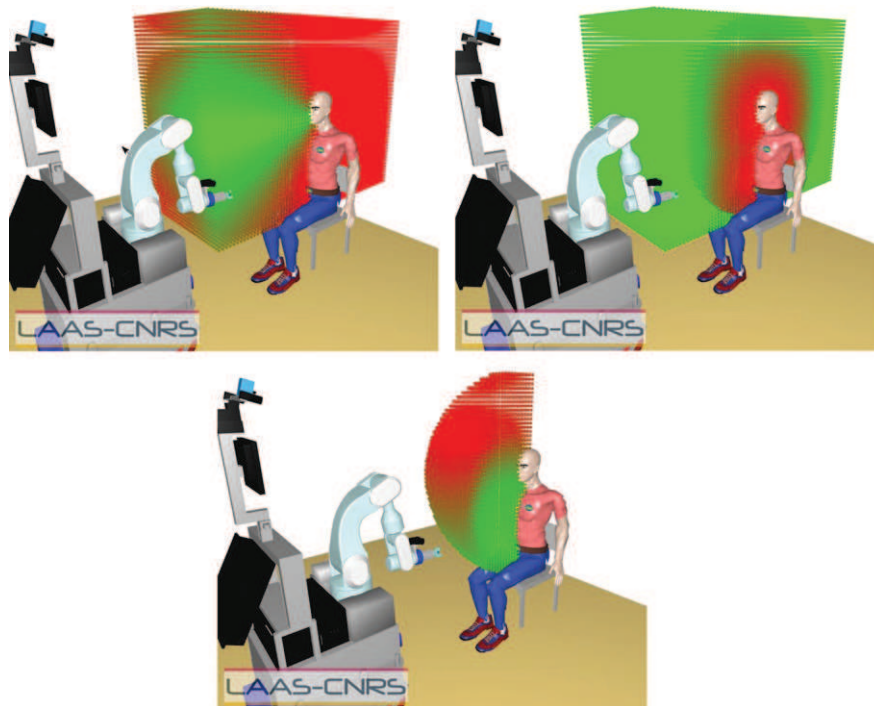


Fig. 2. Three criteria (respectively legibility, safety and physical comfort) to generate ergonomic hand-over motions are presented by cost functions mapped around the human attached to his torso. Top left – Legibility criterion evaluates points according to the difficulty for the human to see and predict the robot arm and the object transfer. Top right – Safety criterion can be mapped as a protective bubble around the human. Bottom – Physical comfort criterion assesses where and when the robot delivers the bottle to the human.

2.3.2. Motion types

Motion-1: with planner, with grasp detection, medium velocity. Our reference motion. The Human Aware Manipulation Planner computes a path according to human's position, orientation and his/her sitting posture. The jerk of the robot motion is limited to 0.9 m/s^3 , acceleration to 0.3 m/s^2 and velocity to 0.25 m/s . Detect-Human-Grasp function is also activated during the motion to allow the human to grasp the bottle whenever he/she wants (Fig. 3). Once the human grasp is detected on the bottle the robot stops, releases the bottle and returns to its initial position. This gesture is designed *a priori* to be the most legible, the safest and to elicit a low physical effort since its trajectory has been planned to deliver the bottle towards the participant's hand in a comfortable manner, with an appropriate velocity and as the bottle was released when the participant grasps the hand.

Motion-2: no planner, no grasp detection, high velocity. The Human Aware Manipulation Planner is disabled and the robot's path is a straight line towards the human without taking into account his/her posture or position. The robot's jerk, acceleration and velocity are not limited. Detect-Human-Grasp function is activated only when the robot reaches its target position so that the human is not able to acquire the bottle during robot motion (Fig. 3). When the human grasps the bottle, the robot arm returns to its initial position. This gesture is designed *a priori* to be the least legible, the least comfortable and the least safest since the trajectory has been planned to deliver the bottle toward the participant in a straightforward motion with high velocity and as it is not possible for the participant to grasp the bottle while the gesture is not over.

Motion-3: with planner, no grasp detection, low velocity. The Human Aware Manipulation Planner computes a path according to human's position, orientation and his/her posture. The robot's speed constraints are four times more conservative than Motion-1. Detect-Human-Grasp function is also disabled until the robot reaches its target position. The human is not able to get the bottle

during robot motion. Once the arm finishes its motion, the human grasps the bottle, and the robot arm returns to its initial position. This gesture is designed *a priori* to be moderately legible, moderately safe and to elicit the highest physical effort and thus the lower physical comfort as its trajectory is planned to deliver the bottle around the participants hand but very slowly, and even though the participant could be tempted to grasp the bottle, it cannot be delivered while the robot motion is not over.

2.4. Procedure

The participant was told that he/she had to take a bottle handed over by a robot in three different manners and that he/she was expected to rate these gestures with a three dimensional subjective scale. Each participant was submitted one time to each motion. The order of presentation of the motions was fully counterbalanced across the participants (Balanced Latin Square). The volunteers were then seated on a comfortable chair at 1.3 m from the robot, sufficiently far from any physical danger but yet sufficiently close to react according to robot motions. The 2 physiological sensors were arranged on the participant's chest and deltoid muscle and the eye tracker was placed on their head. Next, the participant completed a 10-point visual calibration and then had to rest for 3 min to determine the physiological baseline. An exemplary robot motion was shown to the participants in order to familiarize them with Jido and to check participant's understanding of the subjective scale. This training motion was different from the three experimental motions: the planner was deactivated and the robots' motions were generated as a straightforward line towards a predefined position with a medium velocity, and with grasp detection activated. For this exemplary motion, the participant was asked to stand next to the chair, facing the robot (towards front-left of the robot), and was asked to take the bottle handled by Jido and then to rate it with 3 dimensional subjective



Fig. 3. The robot's and human's posture while passing the bottle in the Motion-1 (left) and Motion-2 (right)

scale. After this training, the experimentation begun and the participant was seated back on the chair to face Jido. The arm of the robot was placed on an initial posture with the gripper pointing toward the human. At its initial state, the robot held an orange bottle. Each session lasted about 20 min. After each robot gesture, the participant was asked to rate it with a three dimensional subjective scale.

2.5. Subjective measurements

Self-reports of legibility, safety and physical comfort, rated using a 9-point visual analog scale (1 for very low, 9 for very high), were collected immediately after the end of each motion to assess user's subjective experience. The evaluation of safety concerned the intensity of stress or arousal felt by the participants whereas the legibility rating was linked to the quality and the predictability of the motion. The physical comfort was related to the physical demand required to reach and take the bottle during the interaction.

2.6. Physiological measurements

The ProComp Infinity system (Thought Technology) was used to record two physiological data at 256 Hz: the skin conductance and the deltoid muscle activity.

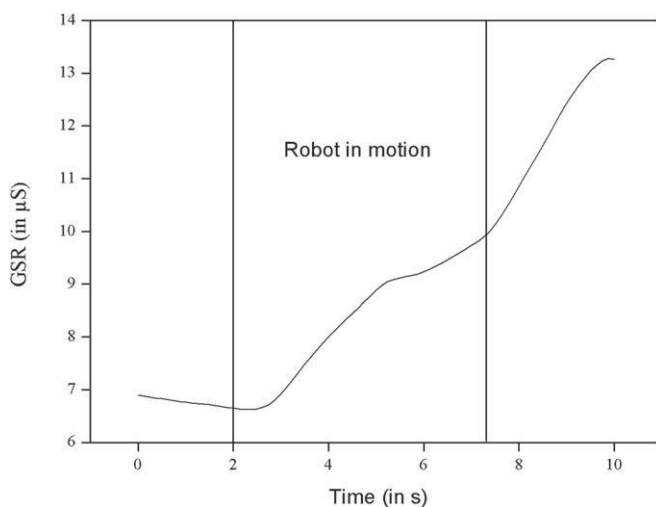


Fig. 4. Typical galvanic skin conductance response during the interaction with the robot.

2.6.1. Skin conductance

The skin conductance was measured using the SCFlex-Pro sensor. The galvanic skin resistance (GSR) were measured in micro Siemens and analyzed off-line. Responses (Fig. 4) were computed as a change in conductance from the pre-stimulus level to the peak of the response. Following information provided by Dawson et al. (2000) (1–4 s latency and 1–3 s rise time), the minimum level occurring within 1–3 s from stimulus presentation was subtracted from the peak value occurring within a 3–7 s window, an absence of response was computed as 0 ($G_{max} [ts + 3; ts + 7] - G_{min} [ts - 3; ts - 1]$).

2.6.2. Electromyogram (E.M.G.)

The deltoid muscle activity was measured with the Myoscan Pro electromyography sensor when the subject raised his arm to take the bottle. The deltoid activity elicited by each Jido motion was calculated using the mean value of the data recorded from the beginning of the gesture of the participant to its end.

2.7. Oculometry: behavioral measurements

A Pertech head-mounted eye tracker was used to analyze subject's ocular behavior (Fig. 5). This device has 0.25° of accuracy and a 25 Hz sampling rate. It weighs 80 g which makes it likely non-intrusive for the subjects during the experimentation. A dedicated software (EyeTech Lab®) provides real time data such as the

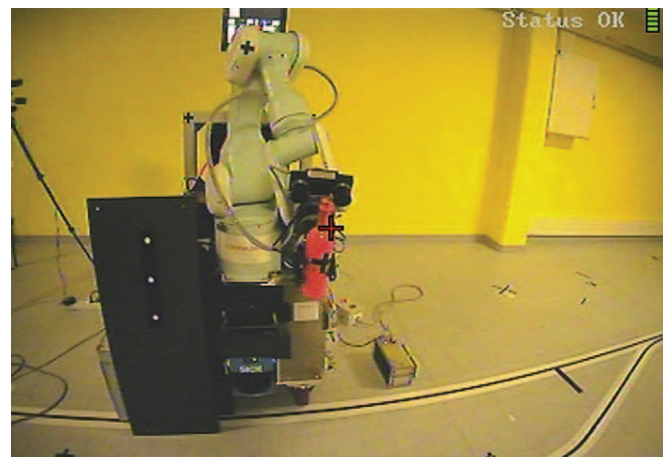


Fig. 5. The subjects were equipped with an eye tracker: the red cross indicates the gaze location. In this example, the subject is focused on the bottleneck.

timestamps, the (x, y) coordinates of the subject's eye gaze on the scene. The data were used to determine the mean eye fixations duration during each robot motion and the number of saccades between the bottle, the robot arm and the rest of the scene.

3. Results

Behavioral and physiological data have been analyzed with Statistica[®] 7.1. We examined the main effects of the three motions on our subjective and physiological variables thanks to repeated measures ANOVAs. We used Fisher's LSD post-hoc for paired analysis. Coefficient correlation computation was carried out using the Bravais–Pearson test to examine the links between subjective assessment and physiological/occulometric measurements.

3.1. Subjective assessment

The repeated ANOVAs revealed strong significant differences between the three motions for all the rating dimensions: legibility, safety and physical comfort (Table 1, respectively $p < 0.001$; $p < 0.001$ and $p = 0.003$).

Fisher's LSD post-hoc paired comparisons have showed that, as expected, Motion-1 was rated as the most legible regarding to the two others (Motion-1 > Motion-2, $p < 0.001$; Motion-1 > Motion-3, $p < 0.001$). Moreover, Motion-1, was also rated as safer than the two others (Motion-1 > Motion-2, $p < 0.001$; Motion-1 > Motion-3, $p < 0.001$). The motion-2 was also considered significantly as less safe than the Motion-3 ($p = 0.021$). Eventually, Motion-1 was also considered as the one that generates the lowest physical effort compared to the two others (Motion-1 < Motion-2, $p < 0.006$; Motion-1 < Motion-3, $p < 0.001$). As expected, Motion-1 was the most legible, the least unsafe and generated the lower effort. On the contrary, the Motion-2 was the most unsafe and the Motion-3 was associated with the greatest effort.

3.2. Physiological and oculometric measurement

Several results have been uncovered by the physiological and oculometric measurements (Table 2). The repeated ANOVAs revealed a main effect of the type of motion on the mean duration of visual fixations ($p = 0.002$). The Fisher's LSD post-hoc showed that Motion-1 has generated shorter mean duration of visual fixations than Motion-3 ($p = 0.032$) and Motion-2 ($p = 0.009$).

Moreover, the repeated ANOVAs revealed a main effect of the type of motion on the number of saccades from the bottle to another part of the robot arm ($p < 0.001$). No eye fixations or saccades from the bottle to rest of the scene were observed during the gestures. Fisher's LSD post-hoc test showed that Motion-3 has generated a higher mean number of saccade than Motion-1 ($p < 0.001$) and Motion-2 ($p < 0.001$) and that Motion-1 has generated a higher mean number of saccades than Motion-2 ($p = 0.049$).

The repeated measures ANOVAs revealed that the GSR was different across the three type of motions ($p = 0.041$). Fisher's LSD post-hoc paired analysis showed that Motion-2 elicited a higher GSR response than respectively the Motion-1 ($p = 0.033$) and than the Motion-3 ($p = 0.023$).

Table 1
Subjective evaluations for each motion.

Subjective variables	Motion-1	Motion-2	Motion-3	p-value
Legibility	7.33 (± 1.18)	4 (± 0.72)	3.58 (± 0.54)	<0.001
Safety	7 (± 0.39)	2.25 (± 1.05)	4.66 (± 0.57)	<0.001
Physical comfort	6.33 (± 0.43)	2.83 (± 0.92)	1.83 (± 1.03)	0.003

Table 2
Physiological sensors findings and oculometry results according to the three motions.

Sensors variables	Motion-1	Motion-2	Motion-3	p-value
Fixations (in m s)	124.00 (± 2.88)	160 (± 15.03)	147 (± 5.41)	0.002
Number of saccades	1 (± 0.960)	0.28 (± 0.61)	3 (± 1.66)	0.001
GSR (in μ S)	1.38 (± 0.39)	3.42 (± 0.78)	1.22 (± 0.33)	0.027
Electromyogram (in μ V)	19.60 (± 3.52)	27.30 (± 5.44)	32.45 (± 6.95)	0.009

The repeated measures ANOVAs performed on EMG data also illustrated an overall difference between the three motions ($p = 0.002$). Fisher's LSD post-hoc showed that Motion-3 generated a higher EMG response than respectively Motion-2 ($p = 0.047$) and Motion-1 ($p = 0.002$).

4. Discussion

The motivation of this research was to validate our reference motion that was designed to be in full compliance with our legibility, safety and physical comfort criteria. The first result was to ensure that the hypothesis that had guided the design of these three motions was coherent with the three dimensional subjective assessment of the participants. The findings showed that Motion-1, the ergonomic reference gesture, has been significantly distinguished as more legible, safe and comfortable than the two others. As previously demonstrated by Kanda et al. (2004), well-coordinated robots are akin to be positively rated by the subjects as they facilitate HRI. On the contrary, Motion-2, the high velocity gesture with no planner, was subjectively assessed as the most unsafe. This evaluation is consistent with the results found by Nonaka et al. (2004) where the participants rated faster "pick-and-place" motions as the most fearing and surprising ones. Eventually, Motion-3 was ranked as the least physically comfortable and the least legible for the subjects as long as its low velocity and the inhibition of the "grasp detection" sensor led the participants to "struggle" prematurely with the robot to get the bottle. These subjective results related to Motion-1 confirmed the efficiency of the grasp detection function and of an accurate velocity to provide the best user experience. Nevertheless it cannot be strictly concluded that the motions generated by our planner are pertinent and acceptable in all situations. But, at least, we assume that, in the context of our experiment, the robot behavior is preferred when it is synthesized by our planner.

The second objective of this study was to assess the impact of the different motions on different physiological parameters and the visual activity. These objective results showed that the three motions could be significantly discriminated by these measurements. Indeed, The GSR response elicited by Motion-2 was respectively superior to Motion-1 and Motion-3 responses. Indeed, Motion-2 led to higher GSR response whereas Motion-3 gesture elicited the lowest GSR response. Regarding the fact that the GSR is a reliable indicator of affect (Codispoti et al., 2001) and arousal (Collet et al., 2009), it may be suggested that the higher GSR observed during the Motion-2 was due to its surprising and stressing effects as it delivered the bottle quickly and toward the participants' face. This confirms the studies conducted by Kulić and Croft (2007) and Takahashi et al. (2001) where high velocity and threatening motions provoke higher GSR than low velocity and non-threatening ones.

In addition, the EMG data showed that the three motions were statistically different: Motion-1 had elicited a lowest muscular activity than Motion-2 and Motion-3. As expected, mean EMG activity for Motion-3 was the highest. Such results were not surprising considering the design of these gestures: Motion-1 had an adequate speed and the bottle was released as soon as the subjects

seized it, Motion-2 imposed a reflex muscle activity to seize the bottle and then Motion-3 led to less physical comfort as the bottle was slowly presented and was not released until the motion ended despite the muscular efforts of the participants to seize it.

Eventually, the eye-tracking measurements have revealed that Motion-2 and Motion-3 led to statistically higher mean fixations time than Motion-1. This may suggest that Motion-2 and Motion-3 were more complex gestures to be perceived as longer mean fixations duration are generally believed to be an indication of a participant's difficulty extracting (Fitts et al., 1950) or interpreting (Goldberg and Kotval, 1999; Just and Carpenter, 1976) information. Interestingly enough, the saccadic activity induced by these two gestures were opposite: Motion-3 has provoked a higher mean number of saccades from the bottle to another part of the robot arm whereas the Motion-2 has elicited the lowest mean number of saccades from the bottle as volunteers were essentially staring at it. In one hand, this decreased saccadic amplitude and concentrated fixations on a single AOI may reveal excessive focusing (Cowen et al., 2002; Tsai et al., 2007) induced by the velocity and threatening features of Motion-2. In another hand, the highest number of saccades toward other parts of the robot elicited by Motion-3 may reveal greatest amount of search (Goldberg and Kotval, 1999) and difficulty to understand when to interact and get the bottle released.

As the experience design was not full factorial, it did not allow to determine the relative contribution of each of the gesture variables as well as their interactions on these objective measurements. Nevertheless it showed that combining such measurements could lead to formalize more precisely the HRI as proposed by several authors (Kulić and Croft, 2007; Liu et al., 2008) and pave the way to adapt in real time the robot motions and reactions in function of the human physiological measurements. Therefore one of our future objectives is to replicate such experiments with more participants and more robot motions in order to complete and refine our approach and to obtain precise physiological thresholds. This will allow us to connect the physiological sensors with our robot for feedback and adaptive automation perspectives as proposed as initially proposed by Rani et al. (2002) and Rani et al. (2004).

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