The Effect of Gravity on Perceived Affective Quality of Robot Movement

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Abstract Non-verbal communication, in particular emotions and social signals, has the potential to improve interaction between humans and robots. Body movement style is known for influencing the affective interpretation of a movement in humans. In this paper the effect of gravity on perceived affective quality of robot movement is investigated. Simulations of a robot arm executing various daily tasks were created. Each task is executed under three different virtual gravity conditions: positive (downward directed force), negative (upward directed force) and no gravity. In a user study participants rated videos of the movement of the robot arm in terms of its emotional content. The robotic arm performed ten different tasks. Two response tools were used for the participants to rate the videos: the AffectButton and the Self-Assessment Manikin. Results show that there was a residual significant effect of the virtual gravity variable on the AffectButton. Moreover, there was a large significant effect of task on the ratings of both the AffectButton and the Self-Assessment Manikin. This indicates that gravity has a small, but measurable effect on the perceived emotional content of even a simple, rather disembodied, robot movement.

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1 Introduction

It is widely accepted that robots are entering our societies and will be ubiquitous in the near future. Robots that exist today already resemble humans [1]. Creating robots that move as humans is, however, a challenging but still distant goal. Replicating human agility requires new types of actuators and power sources. Imitating human's capability for nuanced motion and expressive gesture requires novel control algorithms. Human-like motion also has the potential to mitigate the well known Uncanny Valley [2]. Non-anthropomorphic robots can also benefit from the knowledge of human movement. The first reason for considering non-humanoid expressive robots, is that robots that are specially designed for certain tasks, do not have to be limited to human-like morphology. The second reason is that of feasibility in terms of market economy. At this moment, humanoid robots are developed in research laboratories and are not yet on the consumer market. Simpler non-humanoid robots hold cost-effective designs, allowing for large-scale replication [3]. This paper is a contribution to the field of bodily emotion expression in non-anthropomorphic robotics by analyzing the human perceived effect of virtual gravity on a collection of simulated tasks generated by a class of control laws.

1.1 Related Research

One of the key challenges in bodily emotion expression lies on the multitude of theories that attempt to define emotions and how they can be identified and structured. When it comes to non-verbal bodily expression, different concepts have been proposed on which variables are changed when expressing certain emotions. On the one hand researchers have looked at the different body parts that are used, for example [4–9]. On the other hand studies have investigated the characteristics of the motions of these body parts but also of whole body movement, for example [5, 10–15]. The next development step involved the transition of these ideas into the expression of emotions by animated characters or robots. Again, different approaches exist here. Some studies have focused on mimicking key poses from actors: [16–20], others have used movement characteristics from human motion studies to control virtual characters or robots: [21–24].

There is no complete and agreed view upon a standard for emotion expression in robots. As such there is a need for validated principles that can be used to generate emotions in the bodily motions of robots. Today researches have approached this problem by investigating the use of different variables (e.g. position, velocity, extensity [23]). This paper follows a similar approach, and focuses on the validation of a new parameter: virtual gravity. The hypothesis is that a movement generated with an upright open posture and 'high energy' used to overcome gravity reflect a high level of dominance, pleasure and arousal, while a movement with a low closed posture is perceived in the opposite way. In nature, some land animals, such as grizzly bears, often use upright postures to display dominance. We see this as corroborating our hypothesis. Cuttle fish use flashing patterns of colour in their bodies to signal dominance. This is probably a consequence of their water environment where gravity does not affect the dynamics of sea creatures (they are mostly naturally buoyant). Thus, raising tentacles is probably not perceived as a dominant behaviour in a water environment by other sea creatures. Humans live in an environment strongly affected by gravity. As such we hypothesise that the apparent effect of gravity on the body can lead to the perception of different emotional content.

2 Model-Based Control

In this section we introduce a mathematical model to test our hypothesis: virtual gravity is a parameter that influences the perceived emotion of a generated robotic movement. The model consists of two parts: first the physics-based model of the robot, and second, the mathematical model of the controller.

2.1 Model and Controller Design

In this paper we use a model-based control approach. We consider a full dynamical model of the robotic platform to enable changing the effect of gravity. This effect is implemented by changing the gain on the gravity compensation term. The proposed control law is shown in (1)

$$u = -J^T\left(K_p(x - x_d)\right) - K_d\dot{q} + (1 - \delta)G(q), \tag{1}$$

applied to the standard mechanical model of a robotic manipulator [25], described by

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = u. \tag{2}$$

The control law u is constructed using three elements. The first element $J^T\left(K_p(x - x_d)\right)$ is the task controller part (in practice it consists of projecting a spring-based virtual force in the workspace into the joint coordinates). The second element, $K_d\dot{q}$, realises energy dissipation. The third element modulates gravity compensation. Applying the control law (1) into (2) results in:

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + \delta G(q) = -J^T\left(K_p(x - x_d)\right) - K_d\dot{q}.$$

Knowing that one can write $\delta G(q) = \delta g \bar{G}(q)$, where g is the standard acceleration due to gravity, and $\bar{G}(q)$ is only a function of the kinematics of the robot, then the parameter δ represents the number of virtual g-forces acting on the robot. For example,if $\delta = 0$ the robot is not affected by gravity, $\delta = 1$ results in normal gravity, and $\delta = -1$ results in the effect of a reversed gravity vector. With this control law, the task of the end effector is achieved by the first term, dissipation on the entire arm by the second, and the third term in effect uses the extra degrees of freedom to react to the δ effect of virtual gravity. By changing δ one influences all body parts of the robot between the base and the end effector. A task trajectory can then be executed under different gravity circumstances.

2.2 Implementation

The goal is to create simulations where the effect of a changing virtual gravity vector on the robotic bodily movement is clearly visible. A robotic arm was chosen to execute various tasks. While executing a task, the changing virtual gravity affects the way the body performs the task without interfering with the task itself, i.e. the movement of the manipulator is the same. The full dynamical model of the robotic arm was implemented in Matlab using Lagrangian mechanics with joint angles as the generalized coordinates. It was decided to simulate an industrial looking robotic arm, with 10 degrees of freedom. The model of the arm can be seen in Fig. 1.

The evolution of the joint angles for a given task trajectory described by expression (1) was solved using a standard Newton-Euler integration method with variable sampling rate.

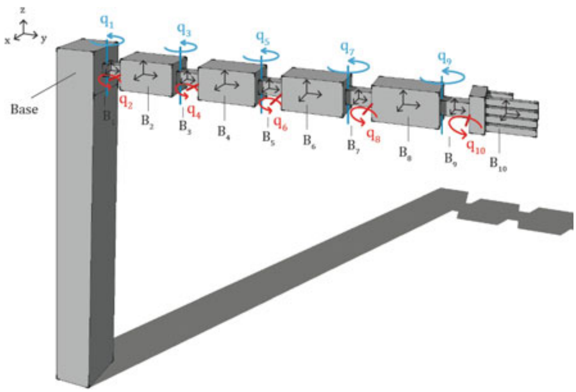


Fig. 1 Model of the simulated arm

3 Methodology

3.1 Simulations

Ten tasks were chosen for the robotic arm. While executing these tasks, the changing virtual gravity vector affects the way the arm performs the task. The next section describes the experimental design choices in more detail, and the steps taken to create the simulation videos.

1. Arms: Two robotic arms are used to execute each task, in order to verify that the responses from the user study are independent of the visual appearance of the arm. A third arm was designed only to use for the start-up test of the experiment. The arms were designed to have industrial features. They purposely have kinematic differences from a human arm. For some tasks, it was convenient to add an human-like hand. The first arm is square-shaped with open centres. The second arm is similar, but has round shapes. The third arm is also round-shaped, but all bodies are of an equal size. Figure 2 illustrates the final design of the three arms.
   All arms are composed of 10 rigid bodies, connected by 10 rotating joints, resulting in 10 actuated degrees of freedom. This over-dimensioned number of joints was chosen to give the arms enough freedom to simultaneously perform the end-effector task in the workspace and result in different body postures for different gravity levels.
2. Tasks: Daily tasks were given to the robotic arm to execute. Ten tasks were designed to be used in the main part of the experiment: closing a book, opening a door, opening a drawer, giving an object, pointing at an object, pushing an object towards a person, replacing an object, stirring a bowl, switching on the light and writing on a blackboard. One extra task, opening a box, was designed and used for the start-up test of the experiment. Different tasks were designed in order to make sure that the responses from the user study would be independent of the type of task. The tasks were selected from the perspective that they do not have an initial emotional content. The selection of the tasks was based on the fact that some include interaction with an object, some include interaction with a person, and some include neither object nor person interaction. Since the focus

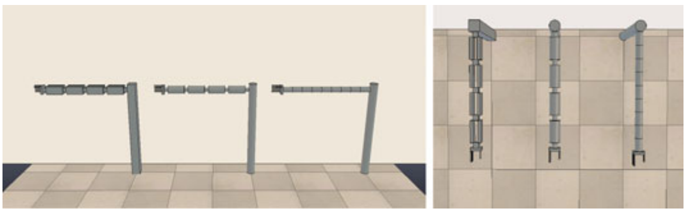


Fig. 2 Geometry of three non-human like robotic arms utilized in the user studies

of this experiment was on the changing effect of virtual gravity in the entire arm movements, all tasks were designed to include movements of the entire arm.

3. Virtual gravity: Three different levels of the virtual gravity vector were explored. Firstly, twice the normal gravity level, secondly no gravity, and thirdly twice the normal level in the reversed direction. These magnitude levels were chosen in order to obtain viewable differences in the simulations.
4. Visualisation environment: The software *Virtual Reality Education Pathfinder* or Vrep was used for the visualisation of the dynamic movement of the robotic arm. Together with the calculated dynamics of the arm, a natural looking scene was created around the robot. This was not only done to make the scene look more realistic, but also to give an indication of the size of the arm. The Matlab model of the arm was recreated in Vrep, using rigid bodies and joints. Six different videos were made for each task, using the combination of two arms and three levels of gravity. All six videos were recorded from the same view angle.

3.2 Experimental Setup

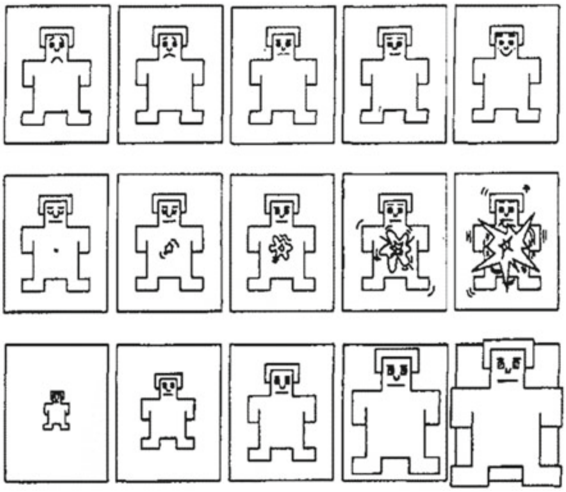
The statistical setup of the test is based on the main question of this research. The main goal of the user study is to see if participants can objectively identify emotional content in the movement of a robotic arm. In other words, it is *not* desired that they see the variations of one task as a result to the changing gravity, and then rate the emotional state while comparing these videos. The same holds for the morphology of the arm. Therefore, it was decided to introduce a “between subject” study for the gravity and the morphology of the arm. The third variable (task), was set up as a “within subject” variable. By implementing the two between subject variables: morphology (two options) and gravity (three options), six experimental groups were created. A website was constructed in order to present the experiment on-line.

1. Response tools: Two response tools were chosen to facilitate the participants to report the perceived emotional content of the robot movement in the simulation. In both tools graphical expressions were used to select an emotion. This is an advantage, since the participants do not have to use words to express an emotion.

   The first response tool is called the *AffectButton (AB)*, created by Broekens and Brinkman [26]. It is an on-line interactive button that one can control with a computer mouse. When moving across it, it changes it’s facial expression. When a certain facial expression is selected, the accompanied values for pleasure, arousal and dominance are saved. Figure 3 illustrates the AffectButton and several examples of affective states.

Fig. 3 The AffectButton with eight example expressions used to report on different levels of pleasure, arousal and dominance

Fig. 4 The self-assessment manikin used to report on different levels of pleasure, arousal and dominance



The second response tool is called the *Self-Assessment Manikin (SAM)*. This response tool was created by Bradley and Lang in 1994 [27]. It asks the participants for a direct score on pleasure, arousal and dominance. It uses a nine-point Likert scale accompanied with five supporting images. The Self-Assessment Manikin is illustrated in Fig. 4.

2. Questionnaire: The experiment was concluded with a short questionnaire. In total seven questions were asked concerning the participants gender, age, nationality and finally expert level in the following four categories: robotics, human movement analysis, acting and the interpretation and measurement of emotion.

4 Experimental Results

All effects are reported as significant at p < 0.05.

4.1 Main Analysis

To identify if gravity has an effect on the perception of emotion in the arm movements presented in the tasks, a multivariate mixed ANOVA of both the AB and SAM together is computed. Using Wilks's statistic, there was a near significant effect of gravity on the ratings of pleasure-arousal-dominance (PAD) for both the AB and SAM, $F(12, 528) = 1.630$, $p = 0.080$, $\eta^2_{partial} = 0.036$. Furthermore, there was no significant effect of morphology on the ratings of PAD for both the AB and SAM. In addition, there was no significant interaction effect between gravity and morphology on the ratings of PAD for both the AB and SAM. There was a significant effect of task on the ratings of PAD for the multivariate analysis, $F(54, 216) = 12.169$, $p < 0.05$, $\eta^2_{partial}$.

The next multivariate mixed ANOVA was executed only for the AB. Results show that there was a significant effect of gravity on the ratings of PAD for the AB, using Wilks's statistic, $F(6, 534) = 2.502$, $p = 0.021$, $\eta^2_{partial} = 0.027$. There was again a significant effect of task on the ratings of PAD for the AB, $F(27, 243) = 14.312$, $p < 0.05$, $\eta^2_{partial} = 0.614$.

Next, the same multivariate mixed ANOVA was executed only now for the SAM. Using Wilks's statistic, there was no significant effect of gravity on the ratings of PAD for SAM. Again, there was a significant effect of task on the ratings of PAD for the SAM, $F(27, 243) = 20.458$, $p < 0.05$, $\eta^2_{partial} = 0.694$.

Furthermore, when looking at the individual dependent parameters in a univariate ANOVA the following results are found. There was a near significant effect of gravity on the variable pleasure of the AB $F(2, 269) = 2.757$, $p = 0.065$, $\eta^2_{partial} = 0.020$. Also there was a significant effect of gravity on the variable dominance of the AB $F(2, 269) = 2.757$, $p = 0.046$, $\eta^2_{partial} = 0.023$. For the SAM, there was a significant effect of gravity on the variable pleasure $F(2, 269) = 3.523$, $p = 0.031$, $\eta^2_{partial} = 0.026$. On the other variables there was no significant effect.

The effect of task was also evaluated for the individual dependent parameters (e.g. AB pleasure, AB arousal, etc.). Mauchly's sphericity test pointed out that sphericity had been violated regarding five dependent variables. Only for the arousal of the AB the sphericity could be assumed. For the five other variables the degrees of freedom were corrected using the Greenhouse-Geisser estimates for sphericity (ε). Results show that for all six variables there was a significant effect of task on each individual variable, as illustrated in Table 1.

Table 1 Effect of task on dependent variables

Variable	Test	p	$\eta^2_{partial}$
AB pleasure	$F(8.248, 2421) = 35.902$	<0.001	0.118
AB arousal	$F(9.000, 2421) = 10.433$	<0.001	0.037
AB dominance	$F(8.301, 2421) = 13.796$	<0.001	0.049
SAM pleasure	$F(8.250, 2421) = 44.093$	<0.001	0.141
SAM arousal	$F(8.389, 2421) = 17.578$	<0.001	0.061
SAM dominance	$F(7.899, 2421) = 7.615$	<0.001	0.028

Since the significant effect of each task was present in all variables, further evaluation was done to evaluate the different effect of each task on the individual dependent variables.

The estimated marginal mean of each task was determined per dependent variable. These means were compared to the mean of each variable. Some of the tasks are more often significantly different from the mean of that variable than other tasks. The number of times the estimated marginal mean differed from the variable mean was counted. In Table 2 it can be seen that task 2, task 3, task 4 and task 5 show significant differences with the means in five out of the six dependent variables. These were the tasks of opening a door, opening a drawer, giving an object and pointing at an object. Task 8, stirring a bowl was rated significantly different for four out of the six dependent variables.

4.2 *Secondary Analysis*

The first part of the secondary analysis concerns the correlation between the two response tools. The results in relation to the differences in demography of the participants have been evaluated in the second part.

Table 2 Number of times of significant different results compared to the the variable's mean. The subscripts on the column headers mean pleasure, arousal, or dominance (e.g. AB_p represents AffectButton and pleasure)

Task	AB_p	AB_a	AB_d	SAM_p	SAM_a	SAM_d	Total
1		Yes			Yes		2
2	Yes	Yes	Yes	Yes	Yes		5
3	Yes	Yes	Yes	Yes	Yes		5
4	Yes	Yes	Yes	Yes	Yes		5
5	Yes		Yes	Yes	Yes	Yes	5
6						Yes	1
7					Yes	Yes	2
8	Yes		Yes	Yes		Yes	4
9							0
10		Yes					1

4.2.1 Correlation Between the AffectButton and the Self-assessment Maninkin

A Pearson's correlation test was executed for the three dependent variables pleasure, arousal and dominance. To do this the means of the different dependent variables were calculated for the ten tasks. These ten means were then compared between the AB and the SAM. There was a significant relation between the pleasure of the AB and the pleasure of the SAM, $r = 0.992$, $p\,(\text{two tailed}) < 0.001$. There was also a significant relation between the arousal of the AB and the arousal of the SAM, $r = 0.799$, $p\,(\text{two tailed}) = 0.006$. Finally, there was a significant relation between the dominance of the AB and the dominance of the SAM, $r = 0.729$, $p\,(\text{two tailed}) = 0.017$.

4.2.2 Demographic Information on the Participants

Gender

In total 275 persons participated in this experiment. 139 (50.5 %) men and 121 (44.0 %) women. Fifteen people (5.5 %) did not specify their gender. Most interesting result was that there was a small significant interaction effect of gravity and gender on the dominance of the AB, $F(2, 248) = 3.466$, $p = 0.033$, $\eta^2_{partial} = 0.027$.

Age

Most participants were between 19 and 40 years old. Nobody above 80 participated. Three people did not specify their age group. No interaction effect analyses were executed regarding the differences in age, since the distribution between the groups was not uniform.

Nationality

It was found that most participant (85.4 %) were from The Netherlands. No interaction effect analyses were executed regarding the differences in nationality, since the distribution between the groups was not uniform.

Expert Level

A participant was named an expert if for all four questions the response was never "None" (answer 1 out of 5). With this criteria 53 participants (19.3 %) were considered to be experts. Most interesting results show that there was no significant effects of gravity neither on the evaluation of the multivariate ANOVA's of the AB and SAM nor on any of the individual dependent variables.

5 Discussion and Recommendations

5.1 *Gravity*

It was seen that there was a significant effect of gravity measured on the AB. Moreover, in the univariate ANOVA there was a significant effect measured on the single variables AB dominance and SAM pleasure. However, it should be mentioned that in all cases this effect was very small.

The intermediate differences between the three gravity conditions were rather small. As a result the estimated marginal means were positioned very close together. We believe that this result arises from the lack of anthropomorphic elements in the arm we have used. In the human, the posture of the shoulders and inclination of the head give many clues to its emotional state. What the results show is that, without prior knowledge, it can be difficult for a human to perceive pleasure, arousal or dominance, in a non-human, non-animal like robot device. This suggests that a reductionist approach to modulating movement may be challenging. For future research it would be interesting to search for the minimum set of anthropomorphic-like elements that can generate the perception of emotional content without requiring a learning/training period by the human.

5.2 *Task*

It was seen that the within subject variable tasks gave large significant effects on both the AB and the SAM. For example the effect of a task on the AB ratings was 20 times larger than the effect of gravity. This can be explained as follows. Participants saw all tasks, hence there is a natural tendency to amplify the differences between the tasks. We postulate that the participants feel the need to 'look for' an affective difference between the perceived stimuli. A related explanation is that some tasks simply are perceived to be more positive (e.g., handing over a cup can be seen as polite or in service of) than others. Because the gravity factor was varied between subject, and task within subject, differences between tasks could be compared but differences between gravity setting could not. The large effect of task is thus a solid indication that we have made the right choice to study gravity as a between subject factor: if it had been a within subject factor participants would have also searched for a meaning and since the only thing they could rate was affect this would have inflated our effect size due to comparison effects.

5.3 Morphology

It can be stated that the effect of morphology was not present in this study. Apart from the very small significant interaction effect of task and morphology on the AB dominance, it can be concluded that the two arms morphologies were rated similarly. This means that the effect of gravity is not related to arm morphology, at least not to the morphologies we tested. For further research, regarding the movement of robot arms that are more or less similar when it comes to number of segments, degrees of freedom and size, this variable can be taken out of the experiment, and the use of only one type of arm would be sufficient. However, different robot bodies should be investigated. For example, robots with a more human-like body, or robots with more than an arm, as the effect of gravity could easily be larger in these cases.

5.4 Final Remarks

In this study, gravity as a parameter was singled out. It was the only variable that was tested in this experiment, while other variables that could influence the emotional perception were kept constant. In other studies on variables affecting the perception of the emotional content of robot movement, mostly multiple parameters were simultaneously tested. The study of Yamaguchi et al. [23] for example used position, speed and extensity. These studies argue that some emotions (anger and joy) could not be distinguished by only one parameter, in their case the velocity of the movement. However, Yamaguchi's research was different in that only four discrete emotions were directly generated, while in this research movements were evaluated by different levels of pleasure, arousal and dominance. With the use of the dimensional scale, more nuance is possible, which creates an opportunity for the nuanced effect of gravity to be measurable. Overall, we are convinced that distinguishing gravity with the used method was a correct way of testing one variable. However, the effect remains rather low. Therefore, future research could focus on implementing the gravity parameter, in association with a set of other variables, as for example velocities and accelerations, together with different control strategies.

One of the elements specific to this research is the deliberate use of a non-anthropomorphic robot. This was done to simplify the computational model, and was also based on research by Sawada [28] who showed that in humans it is possible to recognize emotions in arm movements. However, in this experiment the arm was attached to a fixed structure that was not affected by the changes of the virtual gravity. Mounting the arm on a different structure, possibly mobile, may lead to a better human interpretation.

6 Conclusion

In this paper we have concluded that gravity has an effect on the perceived affective quality of robot movement. We have shown this using a minimalistic setup in which a simulated disembodied robot arm was configured to do a set of service tasks (e.g., picking up a cup, opening a door, writing on a whiteboard, etc.). Participants could only see one gravity condition (e.g., positive, negative, or without) which influenced how the arm movement and posture was executed. Our experimental setting tested the effect of gravity in very strict conditions (i.e., between subject comparison, wide variety of tasks, two robot morphologies, and a disembodied non human-like arm). Therefore, we conclude that gravity can modulate the affective quality of robot movement, even though this effect was small.

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