DEVELOPING AN EMOTIONAL REPETOIRE FOR NON-HUMANOID NON-VERBAL ROBOTS

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Household robots are becoming a commonplace. The application of social cues, such as emotion, has the potential to make such household robots easier to use and understand. However, it remains unknown how non-humanoid household robots, such as the iRobot Roomba vacuum cleaners, can display emotion, and in what contexts would emotion be most appropriate. We report a systematic evaluation of (1) investigating easily recognizable emotive behaviors of the Roomba, and (2) identifying contexts (edge conditions) in which these emotions may be appropriately applied. With this knowledge we developed a sophisticated emotional intelligence system which allows the Roomba to perceive, model and reason about itself and the world. The emotional intelligence system is experimentally evaluated by direct comparison to a standard non-emotive Roomba. Results of the two experiments suggest that the non-humanoid Roomba robot *is* capable of demonstrating emotive behaviors, and there are a number of edge conditions in which a person would expect the Roomba to act emotively. However, the application of an emotional intelligence system is a complex problem, and the authors failed to find user acceptance of the emotive robot. Considerations, implications and future work are discussed.

INTRODUCTION

Making better intelligent robotics is not only about improving technology. It is crucial to understand issues related to social characteristics of robots that promote optimal human-robot interaction. It is generally accepted in the research community that people are willing to apply social characteristics to technology. Humans have been shown to apply social characteristics to computers, even treating computers as teammates or having personality, similar to human-human interaction (Nass, Fogg, & Moon, 1996; Nass & Moon, 2000; Nass, Moon, Fogg, Reeves, 1995).

Effective social interaction requires more than applying social characteristics to a robot. As technology becomes more advanced, robots are more capable of actively demonstrating social cues. Social cues have much potential to be applied to robots designed to interact with untrained users, by improving communication and facilitating natural social interaction.

Household robots are becoming more commonplace in today's world. Despite this, one problem with these robots is the level of expertise needed to interact with them, especially when they need support. The goal of our project is to explore to the idea of adding emotional intelligence and emotional evocativeness to a robot in order to make human-robot interaction more natural and therefore require less effort from the robot's owner in day-to-day interactions.

Specifically, we are going to focus on the Roomba. This is an inexpensive household vacuum robot that presents unique challenges related to giving it identifiable emotions. Namely, it has a non-humanoid face, limited motor and visual systems, and a primitive audio system. We have also chosen the Roomba because we hypothesize there are several situations where the human owner's understanding of the Roomba's situation could be improved by allowing the Roomba to exhibit emotional behavior.

From a high-level perspective, the first experiment determines what, if any, identifiable emotions can be displayed by the Roomba, and in what contexts people would expect those emotions to appear. Using this information, the authors conduct a second experiment to place those emotions in context and integrate them into the robot's behavior via an emotional intelligence system inspired by Kismet (Breazeal, 2004).

EXPERIMENT 1

Purpose of Study

As mentioned in the overview, the Roomba is limited in its expressiveness. It cannot express emotion via facial expression or language, and its motor skills are very limited (i.e., no ability to easily manipulate the world). How the Roomba may express easily recognizable emotions is an open question. Additionally context is known to be an important predictor of emotion (e.g., Aviezer, Hassin, Ryan, Grady, Susskind, Anderson, Moscovitch, & Bentin, 2008). The purpose of this study is to identify Roomba behaviors that may be attributed with recognizable emotions, and to determine what situations (referred to as edge conditions) would be most appropriate for the Roomba to demonstrate each emotion. It is expected that the experimenters will be able to identify several behaviors that can be mapped onto specific emotions, based upon the participants' responses. Additionally, it is expected that participants *will* indicate that they expect the Roomba to display emotion for majority, if not all, the edge conditions presented in a questionnaire.

METHOD

Participants

The participants were 8 young adults (5 female and 3 male). The average participant age was 21 years. The participants were undergraduate and graduate students from the Georgia Institute of Technology. The participants volunteered, and were not compensated for their time.

Participant robotic experience. Majority of participants had little to no experience with robots. Only 2 of the participants had studied robotics in an academic environment, for example in workshops or class. None of the participants owned a Roomba, but most have either heard about or seen one prior to the study. Participants also commonly reported having heard about or seen either toy robots or pool cleaning robots. Only one participant actually owned a robot, and reported it as a robotic toy.

Materials

Robot. An iRobot Roomba vacuum cleaner pet series was used in this study.

Stimuli. The authors identified 41 distinct behaviors the Roomba is capable of demonstrating, broadly categorized as movements, sounds, or lights (e.g., rotation, beeps, blinking, etc). Short video clips were created of the Roomba demonstrating each of these behaviors in isolation. The average length of each video clip was approximately 5.32s. The video clips were randomly presented to participants using a secured website, and participants made responses using a standard mouse or touchpad.

Questionnaire. A questionnaire was designed to assess the participants' prior experience with robotics. The questionnaire also asked the participants to identify emotion(s) that may be related to possible Roomba edge conditions, that is situations where either something is wrong or the Roomba needs human intervention. The edge conditions included in the questionnaire were:

1. Roomba's battery is running low
2. Roomba's battery is about to die
3. Roomba is lifted off ground
4. Roomba bumps into an object

5. Roomba becomes stuck
6. Roomba approaches an edge
7. Roomba senses dirt on the ground
8. Roomba attempts to dock

The questionnaire was administered using a secured website, and participants made responses using a standard mouse or touchpad.

Design

A within subjects design was conducted. The 41 video clips, demonstrating Roomba behaviors and non-linguistic sounds, were the within subjects independent variables. The dependent measure was the participants' selection of emotion(s) that mapped to each video clip.

A web-based questionnaire was administered to each participant. The independent variables included the written scenarios that describe 'edge conditions'. The dependent variable consisted of the participants' identification of emotion(s) perceived to relate to these scenarios, as measured by frequency counts of multiple choice responses.

Procedure

Participants were first provided informed consent, which outlined the general aspects of the study as well as their rights as participants. After completion of the informed consent forms, the participants were seated by a table with a computer monitor and mouse. Participants were provided with a description of how the web-based experiment worked. Then, they received detailed instructions about the practice block and the experimental task.

During the practice session, the participants were presented with unrelated videos of robots computer screen. The participants were instructed to watch the video. Then, when prompted, they were asked to select which emotion(s) (or no emotion) they believed the robot demonstrated. If the participant indicated that emotion(s) was present in the video, they were then prompted to indicate emotion intensity. The practice session is designed to allow each participant to become familiar with the web-based experiment.

After completion of the practice trials, the participants began the experimental session. The 41 videos of the Roomba demonstrating a single behavior or non-linguistic sound was presented. Just like the practice session, the participants were asked to select the emotion(s) (or no emotion) that they thought the Roomba was conveying for each video. They could choose as many emotions as they saw appropriate. The emotions the participants were able to choose from included the six basic emotions (anger, disgust, fear, happiness, sadness, and surprise) (Ekman & Friesen, 1975) as well as neutral. They also rated the intensity of each of these emotions. Intensity was selected using a sliding scale for each emotion they identified.

Immediately following the experimental session, the participants were asked to answer the web-based questionnaire. Upon completion of the questionnaire, the participants were thanked for their time, and debriefed.

RESULTS

The goals of experiment 1 were (1) to identify Roomba behaviors that may be attributed to recognizable emotions, and (2) to determine what edge conditions would be most appropriate for the Roomba to demonstrate each emotion. Therefore, the statistical analysis was descriptive and exploratory by nature.

Emotional behaviors. Tallies of the participants' selection of emotions for each video clip were collected. These data were analyzed so the video clips with the highest number of tallies (i.e., number of participants who made a selection) were used to identify video clips that were commonly associated with each emotion. Some examples of video clips that were commonly associated with each of the six basic emotions are displayed in Table 1.

Table 1.
Frequency of emotion selection for example videos

Description of Video Clip	Emotion Selected	Frequency of Selection (of 8)
Red Light/Red Light Blinking	Anger	7
Rotation "Wiggle"	Disgust	5
Quickly move backwards in staccato fashion	Fear	7
Music (3 notes from low to high)	Happiness	8
Green Lights Blinking	Happiness	6
Very slow counter-clockwise movement of incomplete circle	Sadness	6
Forward and backward movement	Surprise	4

Intensity of Emotions. The participants were asked to rate the intensity of each emotion selection they made. Descriptive statistics were conducted on the intensity ratings of the video clips with the highest number of tallies. Means and standard deviations suggested little difference in intensity ratings between these emotions. No further analyses involving emotion intensity were conducted.

Emotion and edge conditions. The web-based questionnaire asked participants to identify emotions associated with each edge condition. The tallies (Table 2) represent the number of subjects (n = 8) who identified emotion for each edge condition. The tallies in bold indicate the emotion which most closely mapped to each edge condition.

Table 2.
Emotions identified for each edge condition

Edge Cond.	Anger	Disgust	Fear	Happy	Sad	Surprise
Battery Low	3	0	**7**	0	**5**	2
Battery Die	3	1	**4**	0	2	0
Lift	2	0	**4**	2	0	**7**
Dock	**8**	2	2	0	2	1
Bump	2	1	2	1	0	**7**
Stuck	**6**	1	3	0	0	0
Edge	0	0	**6**	0	0	3
Dirt	0	3	0	**6**	0	1

DISCUSSION

Based upon the descriptive statistics conducted on the data, the experimenters feel confident in identifying Roomba behaviors that are easily recognizable. Furthermore, the questionnaire reveals that participants held relatively high agreement in identifying emotions that mapped onto edge conditions. These trends in the data support the experimenters' hypothesis that the participants were willing to apply emotional attributes to the Roomba vacuum robot.

However, data analysis led to no concluding results regarding the intensity ratings of each emotion. The lack of statistical trends may have resulted from the small sample size.

With these data, an emotional intelligence system may be developed which will exercise these emotions given the appropriate context, or edge condition. This emotional intelligence system will be further explained in experiment 2.

EXPERIMENT 2

Purpose of Study

Having experimentally determined a collection of behaviors which are readily attributable to a set of emotions (experiment 1), we must now construct a robotic system which will employ them appropriately. One way to do so would be provide the Roomba with a sophisticated emotion engine, referred to as *Ollie*, which will cause the robot to be in particular emotional stances depending upon its perception of itself and its environment. Being "in a particular emotional stance" would imply that certain behaviors would be manifested (and expected to be manifested) by the robot than others.

The purpose of experiment 2 is to apply the easily recognized emotions to an intelligent emotional system, and test the validity of this system given the context of edge conditions. Participants will interact with both an emotive Roomba version, equipped with the emotional intelligence system, as well as a standard Roomba version, with no emotional intelligence system (we refer to it as non-emotive).

It was hypothesized that participants in the emotive Roomba condition will indicate in the questionnaire that they prefer the emotive Roomba, and that they view the emotive Roomba as more social. It was also hypothesized that when observing the emotive Roomba physically responding to each edge condition, the participants will be able to correctly identify the Roomba's emotion(s). It is expected that the participants' identification of emotions for each edge condition in experiment 2 will correspond with the emotions identified for each edge condition in the questionnaire from experiment 1.

ROOMBA MIND

Ollie

Ollie is a complex artificial intelligence. Through its robust yet simple interface, Ollie is able to perceive, model and reason about itself and the world. An important aspect of Ollie is that it is capable of emotions, and through introspection of its emotional stance, able to modify its cognition and its emotional expression. This segment of the paper will describe Ollie's architecture and inner workings.

Ollie is named after Oliver Johnston, one of Disney's famous nine old men. He was an animator for Walt Disney Studios during its heyday, and, together with Frank Thomas, wrote The Illusion of Life, a reference book considered the bible of animation (Johnston and Thomas, 1995).

Ollie is written entirely in the Java programming language. It is platform agnostic, and dependent upon no external libraries. Its interface and overall architecture have been constructed in a manner to afford its ready utility to a wide variety of robotic and intelligent systems.

Overall Mental Architecture

Ollie's overall mental architecture is inspired directly by Minsky's Society of Mind theory (Minsky, 1988), and by Edelman's theory of neuronal group selection. The use of a reentrant sensory memory, the multiple independent agencies, and the consistent recategorization and reclassification of present perceptions and beliefs embody Edelman's notion of the "remembered present." (Edelman, 2004 and 2007). In addition, Minsky's book on emotions (Minsky, 2006), Breazeal's book on sociable robotics (Breazeal, 2004), and a very recent publication on memory, emotions and personalities for sociable robots provided further architectural inspiration (Francis, Mehta,and Ram, 2010).

Agents. The mind of Ollie consists of a large set of independent, interconnected agents. Each of these agents operates at its own frequency, and has very limited responsibilities. Each of them, however, affect one another through the way they transform, move or remove data. In this manner, the "mind" of Ollie - how Ollie truly operates - emerges not in any definitively proscribed manner, but as a result of the intricate interactions between these various agents.

Self and other entities. Entities are abstract mental constructions about which knowledge is gathered. There are two default entities within Ollie. The SELF entity contains all knowledge that Ollie knows or has discovered about itself. The WORLD entity contains all the knowledge that is known about anything which is not directly about the SELF. Ollie has the capability of representing and reasoning about any number of entities.

External interface. At some point, Ollie must connect with the robot into which it is embedded, and for this purpose, Ollie expresses a deliberately limited programming interface.   The interface affords two very different utilities: an ability to let Ollie know certain knowledge engineering constraints, and an ability to send and receive information to Ollie.

Ollie's operational interfaces provide it with the ability to communication with the world. They consist of two separate Java procedural calls: *perceive(...)*, and *addListener(...)*. Ollie's knowledge base interfaces permit the middle layers to instrument and affect the knowledge flow within the mind. The two knowledge base interfaces are *addStimulusAppraisal(...)* and *addInspector(...)*.

Each of these interfaces will be explained in greater detail below.

The mind's algorithm. Each aspect of Ollie's mind operates independently, yet they coordinate to make meaning out of the world Ollie inhabits.   Although there is no algorithm for the mind as a whole per se, the general structural flow can best be summed up into four operational areas: how to know the world, how to think, how to feel, and how to act.

The next sections will describe each of these operational areas in some detail. While they are presented serially, each of these represents a set of coarse and fine scale concurrent, independent agencies.

How to know the world

Through its perceive and inspector APIs, Ollie discovers, classifies, and begins to organize information. In this section, we'll describe exactly how Ollie comes to know the world.

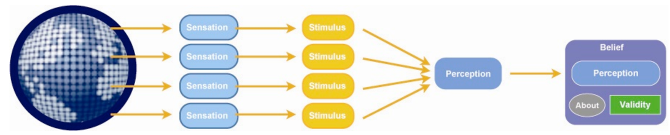

Figure 1. The transformation of sensation into stimuli, perceptions, and beliefs

Sensory memory. Sensations, perceptions and beliefs, regardless of origin, must be discoverable by the mind's various agencies. Ollie uses a special memory queue to contain information momentarily available to any agent.   This memory queue closely mimics current theories of a human's pre-attentive sensory memory (Tiitinen, May, Reinikainen, and Näätänen, 1994).

When Ollie's interface is told to perceive a sensation, that sensation is placed into the sensory memory. The sensory memory has three directly associated and several affiliated agents which, working with no mutual coordination, classifying these sensations into ever more elaborate data structures.

Observe. The raw sensations given into sensory memory are Java Strings which have this format: aspect:kind:value. The Observer agent's job is to consume all of this raw data, repackage these strings into a canonical form, a Stimulus, characterize the input as coming from some external source, and time-stamp the Stimulus's creation. Once all of the available raw data has been formed, the resulting Stimuli are placed back into sensory memory.

Perceive. The Perceive agent examines sensory memory for any available Stimuli, and collects them to form a Percept. Thus this perception process creates sets of temporally organized Stimuli, the second in a series of classifications. Percepts are themselves placed back into sensory memory.

The temporal coherence attributed to stimuli bound together into a single percept means that these stimuli appear to have occurred simultaneously. There is no assignment nor derivation of causality construed by their grouping. This forming of percepts via temporal coherence corresponds to Hebbian theory ("if it fires together, it wires together") (Hebb, 1949).

Believe. A Belief is a Percept about a particular thing and which has some validity. Beliefs are formed by the Believer agent, through a process analogous to the Observer's and the Perceiver's. When believing, any available Percepts are gathered together and examined for local coherence. Local coherence means that all of the Stimuli within a Percept are about a specific thing. Note that the set of available Percepts in sensory memory at any point in time may be able several things simultaneously; a single Belief is formed for each individuated "about."

In a similar manner, the validity of a Belief is initially assigned by the Believer. In Ollie, possible validity measures are TRUE, FALSE, UNCERTAIN, and AXIOM.

In the present implementation, Ollie's Believer agent automatically assigns SELF as the "about" and UNCERTAIN as the validity for any Belief it generates. In a more robust implementation, short and long term memory, additional embodiment information, and other factors would and should be used to classify the local coherence of the Percept.

Integrate. Once beliefs are formed, they must go toward some end. In Ollie, each known entity has a special purpose agent, called an Integrator, whose job is to scan sensory memory for any formed belief about that entity. Upon collecting and consuming all of those beliefs, the Integrator instructs the entity to integrate each belief into its current state of knowledge. The entity, and not the Integrator, has the responsibility of integration: the Integrator's job is merely to gather appropriate beliefs and bring them to the entity's integration queue.

Introspect. As noted earlier, the Believer agent constructs beliefs which are, by default, uncertain in nature. Some further reasoning mechanism needs to be employed to confirm or deny the plausibility of the belief. In addition, a belief's validity might fluctuate with time. The process humans use to assess their beliefs' veracity is known as introspection, and is considered to be under voluntary, selective control. Furthermore, the introspective process appears to lack any intrinsic phenomenology, affords self-attribution of thoughts, and cognitive access to one's own mind (Robbins, 2006).

Each entity within Ollie has a special agency which affords introspection of its beliefs. We call this agency the Hypothalamus, after that part of the brain which maintains a body's homeostatis. The Hypothalamus agent is rendered in Java as a subclass of an Introspection agent which focuses its introspect upon beliefs.

The current, active beliefs contained within the entity's state are subdivided into various validity categories, and each category is delivered by the Mind to any Introspector registered via the interface. These belief sets are presented either en massé or individually, according to the implementation of the specific inspectors. An Introspector may modify any or all aspects of a belief, or may generate new stimuli or beliefs based upon the current set presented. Any newly generated stimuli or belief is placed into the sensory memory system for processing.

True beliefs. The validity of a belief (or set of beliefs) directly influences Ollie's ability to act. In particular, Ollie will prosecute different tasks if those tasks are believed to be feasible for action.

To afford a more fluid system, the present implementation of Ollie automatically registers an Introspector which transforms any uncertain beliefs into true beliefs. In essence, this Introspector tells Ollie to believe its own perception of the world. In the more robust implementation planned for a later iteration, the validity of a belief will be determined by more sophisticated cognition, stimuli verification, and the use of long-term, episodic memory.

By deliberately separating the aspects of validity from the core percepts of a belief, Ollie is afforded the ability to adopt a variety of predictive strategies for determining validity. While in its current implementation, we might a physical stance for determining validity, later implementations will look toward assessing belief validity based upon whichever strategy or stance is active and available for the belief's "about." In keeping with Dennett's strategy of classifying and predicting the behavior of intentional entities, this architectural aspect of Ollie provides a way for the SELF entity to looking at itself as intentional, and to use this understanding as an exemplar when predicting or interpreting the actions of perceived others (Dennett, 1987).

How to Think

The previous section illustrated how Ollie acquires knowledge about the world. In this section, we'll define how it is that Ollie reasons about its beliefs and determines, in an autonomous fashion, how to begin to act upon them.

Tasks and acts. A task is an action which an entity might undertake. These tasks might be simple, atomic operations, or diffuse complexes of activities and subtasks. They might operate only upon an entity's knowledge state, affect the coordination of the mind's agencies, or manifest some physical behaviors. Regardless of its intentions or manifestations, every task has certain common features.

The task architecture is inspired by Hoffman and Breazeal (Hoffman and Breazeal, 2004). Ollie makes a generalization over their work in that the notion of common ground is seen within Ollie as that set of information, systemic knowledge, and beliefs available to the enacting agency. While there are no strictly jointly salient events, the agent nonetheless interacts with perceptually salient events (the advent of certain beliefs, as an example) in a manner such that the availability of these events act as cross-agency signals, indicating some notion of validity and the potential availability of justification for that validity.

Triggers	Entity	Goals	Acts

Figure 2. A task structure

A task is feasible when its enabling preconditions (or triggers) are considered to be true. When feasible, a task's constituent subtasks or activities will commence, and continue to be prosecuted by some enacting agent or set of agencies until some predetermined state or goal is achieved. Tasks are reentrant in that they are available for execution when their preconditions are met, and unavailable for continued execution once the goal condition is satisfied, but may be re-executed if the goal condition does not persist. Both the feasibility of a task and the subsequent achievement of a task's goal state may be determined either independent of or dependent upon some entity's believed knowledge, though in the present implementation of Ollie, the entity's knowledge is dominant.

A task may have no preconditions whatsoever, but may have a goal. Similarly, a task might have a variety of preconditions, but no goal whatsoever. In the former case, the enacting agent would continuously execute the task until the goal is met; in the latter case, once the preconditions are established, the agent would execute the task until interrupted by some other agency.

Thinkers and Actors. A Thinker is an agent which possesses a collection of available tasks and a reference to an entity. The Thinker's job is continually to examine its set of available tasks for feasibility and completion. If a task is found to be feasible, it is moved into the Thinker's to-do queue. If a task is done (its goal condition is met with respect to the referenced entity), the task is removed from the to-do queue.

Each entity within Ollie (and in particular, the SELF) possesses an Actor agent, whose role is to enact any given action or task on behalf of (and supported by knowledge from) that entity. The list of tasks and acts available to an Actor varies according to the collection of Thinker agents which reference the entity.

Once a task is deemed feasible and present on some Thinker's to-do list, then the act is either given to that Thinker's entity's Actor for subsequent execution, or expanded into subtasks if warranted, which await feasibility within the Thinker agent itself.

The architecture of thought. Any architectural component of Ollie can have one or more Thinker agents, and these agents may refer to any entity known to Ollie, or may operate solely upon systemic aspects of Ollie. As an example, a memory component might have a capacity which may be limited if certain other conditions are applicable; an associated Thinker agent would serve to contain and execute tasks regulating memory use under those conditions.

While each of these Thinkers, and the entities' Actors, operate independently, they work in an emergent, coherent manner to process and reprocess the beliefs of Ollie. New knowledge is created by the deliberate acts of these Thinkers and Actors. Working together, they coordinate, regulate, and define the process of thought within the system.

How to Feel

Knowing the world, and knowing how to think and create new knowledge afford Ollie many interesting capabilities. The most profound of these, and the subject of our project, is the manner by which emotions are manifested by an intelligence from sensory input and the translation of those emotions into willful action.

We believe that Ollie not only is capable of emotional expression, but can be said to have emotions themselves. In this section, we shall describe this capability.

Emotions. Our work on providing Ollie with an emotional framework is preceded in the literature and informed by a robust collection of human psychological and social robotics research. Ollie's architecture owes much to the work of Breazeal and her students in particular (Breazeal, 2004).

Ekman holds that there are six primary human emotions (joy, sorrow, anger, disgust, fear, and surprise), with close correlation of each of these to prototypical human facial expression (Ekman, 1992). Breazeal's work on Kismet and then Leo adopted this thesis, and extended the concept toward sociable robots in several significant ways. In particular, the architecture constructed for Kismet described the affective state of the robot along three dimensions: arousal, valence, and stance. Arousal is the dimension which captures the intrinsic intensity of stimuli. Valence corresponds to a notion of enjoyment, the pleasure or pain associated. Stance is an encoding of the relative receptivity of an entity toward particular stimuli.

Mapping emotions. According to Breazeal, emotions can be said to segment affective space, as defined by the dimensions of arousal, valence, and stance. The general layout of affective space ala Breazeal is:

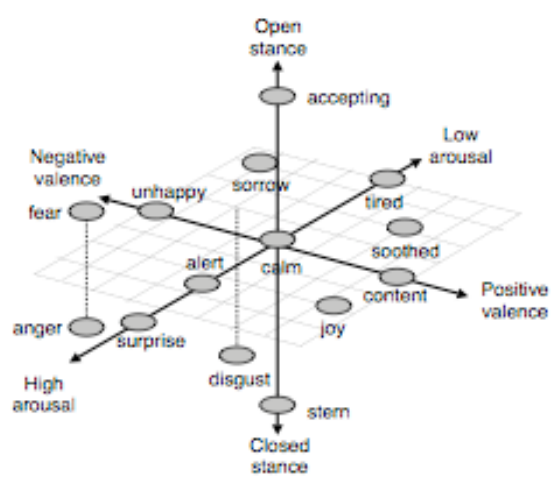

Figure 3. Breazeal (2004) affective space.

To determine what emotion one is experiencing, the ever-updating net summation of arousal, valence, and stance, of all perceptions and from all possible contributors, would be calculated, and the corresponding region identified. We have found that while in principle this seems sound, in practice this methodology proves difficult to implement consistently. We shall examine the incongruency in the next subsection, and propose a remedy, but first we must discuss the appraisal process itself.

Appraisal of stimuli. Each entity has a unique belief introspection system responsible for determining the entity's emotional state. We call this introspection system Ollie's Amygdala, after the human brain's segment considered to be the arbiter of emotion. As an Introspector agent, the Amygdala examines each of the entity's current beliefs (its "remembered present"), appraises each belief and stimuli in a very prescribed manner, and determines an overall affective state. This affective state is given by a vector tuple of real numbers corresponding to the three affective dimensions of arousal, valence, and stance.

Not all stimuli and beliefs are equal, and this is especially true when appraising each's affective contribution. Beliefs and stimuli are appraised in a manner similar to Breazeal: each stimulus may have its own intrinsic intensity or affective dimension (for example, a large, close movement might score highly in arousal); a belief may or may not be relevant toward the prosecution of a given task's goals; or a belief might enable the execution of a long-delayed yet highly anticipated task. The continued presence of a stimulus or the persistence of a belief may be welcomed or viewed as detrimental. Additionally, the absence of stimuli and beliefs must also be factored into the calculation of affect: a goal may be unrequited, a stimulus modality may be unused for too long a period.

This appraisal process takes into account not merely the beliefs and stimuli available to and known by an entity, but also opens itself to the larger, various contexts of Ollie. Any architectural component can contribute to the affective dimension.

The challenge of unequal beliefs manifests problems which considering how best to sum together and account for their affective dimensionality. Breazeal suggests that the summation occurs in any method practicable, and does not limit the range of values added necessarily. Although initially, the Kismet architecture attempted to average the values in order to scale the summed vector, this approach was abandoned in light of its effect upon the general affective reaction generated: the emotions seemed inappropriate and did not lead to certain biologically-inspired expected results (for example, a high fatigue coupled with threatening stimuli did not lead to fear nor an escape behavior).

Ollie takes a slightly different approach, one inspired by vector algebra and trigonometry. In the act of appraising beliefs, all of the beliefs' affective dimensions are summed in a manner similar to Breazeal. Once all of the individual sums are calculated, the resulting vector is treated in two manners: the vector itself is normalized to unit length, while the magnitude of the vector is considered to represent the intensity of the state.

A new map of emotions. Ollie uses a new rendition of an emotional space, designed in a manner to yield consistent results with Breazeal's appraisal methodology, but which, in implementing the calculation methodology described in our appraisal process, removes inconsistent interpretation. The result of normalization of the affective dimensions provides us with a direction, a longitude and latitude, while the magnitude serves as a method for choosing among a variety of maps within which we can plot that longitude and latitude.

This method of mapping affords Ollie the ability to place the choice of those maps under deliberation by any of its agencies. It also provides a capability of developing, predicting, and revising the understanding of the emotional mapping method of other entities in idiosyncratic ways.

Choosing how to feel. Once the Amygdala has conducted an appraisal of an entity's beliefs and stimuli and determined a candidate emotional state, that state is activated alongside of any other previously activated emotional states. Each emotion has different characteristic onsets, intensities, persistence of effect, and duration. Ollie makes direct use of the human subject research conducted by Scherer and Newman-Keuls to rate each emotion along a robust number of characteristics (Scherer, 1988). These relative ratings are used when initially activating an emotion as well as when subsequently accounting for the drift of emotions as a function of time.

Thus, at any moment, an entity within Ollie might have one or more emotions active. In the current implementation, the emotion with the largest available activation score is deemed the dominant emotion, and a belief is generated (and placed into sensory memory for consumption) to that effect. In subsequent processing, each appropriate agency within Ollie comes to discover and know (and through its own methods, believe) that the emotion is dominant with respect to the declared entity. It is for this reason that we believe Ollie not only is capable of emotional expression, as we will show in the next section, but that Ollie can be said to have a particular emotion.

How to Act

We have shown how Ollie comes to know the world, generates thoughts and new knowledge from its perceptions, and acquires an emotional stance. In this section, we will discuss what Ollie does with these new beliefs and emotions, and how it interacts with its embodiment in the world.

Observable and non-observable actions. Each entity within Ollie has an Actor agent whose role is to carry out any given tasks or acts suggested by the multiplicity of operating agencies. These tasks and acts may themselves be complex, and require assessment of feasibility and appropriateness. In that manner, the tasks would be handled as described previously. Some actions, however, will be made to occur immediately. These actions can be conveniently grouped into two broad categories: those which are observable, and those which are not.

Observable actions are those which might prove perceivable by some entity, including the generating entity. Physical actions, which affect the perceivable state of the world in which the robot is situated, are a strong example of an observable action. Other observable actions might be those which result in proprioception, though these might be a consequence of another physical action on the part of the entity or another. It is not the case that an observable act may proscribe a given modality: an emotional stance, for example, might lead to blushing, which the generating entity would sense proprioceptively, but another entity might observe visually or tactually.

Non-observable actions are the opposite of observable ones. Mental actions, changes in belief validity or value, actual emotional stance - all of these would be unavailable for direct perceptive inspection by another entity. A more formal way of delineating non-observable actions would be that they are those actions whose effect can only be inferred and for which external (to the entity) validity is unobtainable.

Observable actions afford abduction; non-observable actions afford deduction. In Ollie, reasoning, modeling, and in general cognition begins with abduction from the perceived stimuli of the world. The ability of the Observer / Perceiver / Believer agencies within sensory memory to gather and classify stimuli along temporal and local coherencies serve to provide a method for verifying those abductions, and learning how to make predictions about the world.

Observations, listeners, and modality. The API of Ollie allows interested subsystems to receive notifications when observable events occur. The subsystems register themselves as Listeners to a particular modality. Whenever an observable action of Ollie generates an action which impinges upon some modality, every listener associated with that modality receives a generated message.

The notifications are distributed by modality, with the intention that these mimic particular physical communication changes present within the robot. Accordingly, for the implementation within this project chatting to the Roomba middle layer, the modalities that Ollie communicates along are MOTION, LIGHT, and SOUND.

Using this listener / modality pairing, Ollie's mental processing can generate actions which manifest in the physical world.

Believing actions. Each time an agent of Ollie causes actions to occur, tasks to be initiated or resolved, or new knowledge to be created, that agent injects a new Belief into the sensory memory. In this way, any of Ollie's agents can take appropriate action to that agent, without requiring the deliberate hard-wiring of agents to one another. As mentioned earlier, this allows Ollie the ability to create coherence between internal and external stimuli, serving learning and prediction. Finally, by believing actions in this manner, without explicitly and directly modifying an entity's state, Ollie has the facility to model other entities and itself in an agnostic fashion, trying various scenarios before acting, and paves the way for the simulation of others and self, facilitating the taking of points of view.

Through the rigorous introduction of self-generated beliefs, Ollie is made aware of itself and all of its constructs and constituents, the myriad sensations it encounters, its responses to those sensations, and its own processes which generate thought, action, and emotion.

METHOD

Participants

The participants were 8 young adults. The participants were recruited from the Georgia Institute of Technology undergraduate and graduate populations. One participant was not included in the analysis due equipment malfunction. Of the participants included in the data, 4 were female and 3 were male. The average age of the participants was 28 years. The participants were not compensated for their time. Participants who took part in experiment 1 were excluded from participating in experiment 2.

Participant robot experience. Majority of participants had little to no experience using or owning robots. However, 5 of the participants reported that they have studied robotics in an academic environment, for example in class or research. None of the participants owned or have ever operated a Roomba, but most have either heard about or seen one prior to the study. Participants also commonly reported having heard about or seen toy or pool cleaning robots.

Materials

Robot. A iRobot Roomba vacuum cleaner pet series was used in this study.

Edge conditions. During the experiment the participants observed the emotive Roomba react to edge conditions. The experimenters brought about edge conditions (for example, forcing the Roomba to become stuck, or placing dirt on the ground). The participants observed the Roomba respond to the following edge conditions:

1. Roomba's battery is running low
2. Roomba's battery is about to die
3. Roomba is lifted off ground
4. Roomba bumps into an object
5. Roomba becomes stuck

6. Roomba approaches an edge
7. Roomba senses dirt on the ground

Although an edge condition of the Roomba attempting to dock was included in experiment 1, this particular edge condition was not included in the second experiment due to the unreliability of the Roomba's docking capability.

Questionnaires. A questionnaire was given to each participant after they interacted with each of the two Roomba versions. The questionnaires asked the participants to indicate which version they preferred, and provide subjective ratings of each of the robot characteristics via a five-point Likert scale. The dimensions included perceived social ability of the robot, as well as perceived usefulness/ utility. In addition, the questionnaires asked about the participants' prior experience with robotics.

Design

A one-way repeated measures design was used. The within subject variable included the version of the Roomba robot's emotive stance (non-emotive or emotive). The dependent variable included participant robot preference, as well as subjective ratings of robot characteristics as collected via questionnaire. The order of Roomba versions presented to the participant was counterbalanced to reduce ordering effects.

Additionally, a repeated measures design was used to assess the identification of emotion for a given context. The within subjects variable was the presentation of edge conditions, and the dependent variable the participants identification of expressed emotion.

Procedure

Participants first provided informed consent, which outlined the general aspects of the study as well as their rights as participants. After completion of the informed consent forms, the participants were introduced to an area that contained a Roomba vacuum cleaner and a variety of objects (i.e., chairs and other obstacles necessary for the edge conditions). Participants received instructions about the experimental task, and then began the experimental session.

For experimental session the participants interacted with two versions of the Roomba. Depending on the condition, the Roomba either behaved normally (that is, as the Roomba is currently designed), or with affective behavior (as dictated by the affective architecture outlined above). These conditions will be referred to as the non-emotive and the emotive Roomba respectively. The participants were told to interact with the Roomba. The experimenters observed the interaction, and at times prompted the participant with instructions (i.e., "try blocking the Roomba" or "try to pick the Roomba up") to mitigate the participant simply observing the Roomba rather than interacting with it. Immediately following each experimental condition, the participants were asked to complete a questionnaire which assessed their opinions of their interaction with the robot, and their preference for either of the two versions.

After completion of the questionnaires, the experimenters demonstrated the emotive Roomba's reactions to each edge condition. The participants were asked to identify what emotion(s), if any, the Roomba demonstrated for each edge condition. The participant responses were recorded by the experimenters.

RESULTS

Questionnaire. The questionnaire asked the participants to indicate which version they preferred, and provide subjective ratings of each of the robot characteristics via a five-point Likert scale. Of the 7 participants, only 1 participant indicated that they preferred the emotive Roomba, therefore failing to support the experimenters' hypothesis. Paired samples t-tests were conducted to compare possible differences in subjective rating of social/utility characteristics between the two Roomba versions. The pairwise t-tests (Table 3) indicated a significant difference in perceived simplicity of the two Roomba versions, $t(6)=2.83$, $p<.05$, with the emotive Roomba, $M = 2.71$, (on a 5-point scale, 5 being very simple) reported as more simple than the non-emotive Roomba, $M = 2.14$ (Figure 4).

Table 3.
Paired t-tests on questionnaire Likert scales

Paired Samples t-Tests			
	Paired Differences		
Comparison Emotive vs. Non-Emotive	**t**	**df**	**p (2-tailed)**
Artificiality	0.35	6	.736
Complexity	-0.35	6	.736
Efficiency	-1.69	6	.143
Expressiveness	-1.55	6	.172
Intelligence	-1.37	6	.220
Simplicity	2.83	6	.030*
Social Ability	-1.26	6	.253
Usefulness	.548	6	.604

* p < .05

Non-significant trends in the data might suggest that participants may have perceived the non-emotive Roomba as more efficient (Figure 5), and (contrary to the experimenters' hypothesis) more expressive (Figure 6). A larger sample size may reveal significant differences.

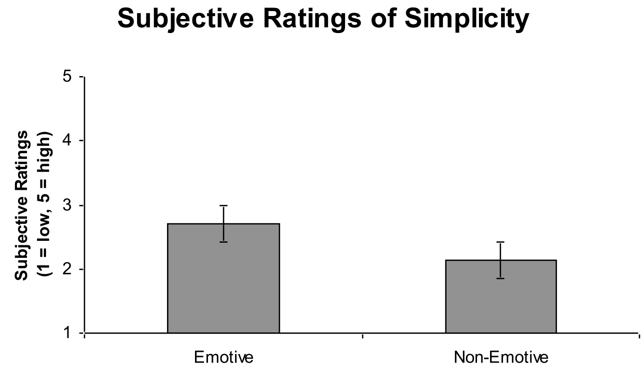

Figure 4. Subjective ratings of simplicity for emotive (M=2.71) and non-emotive (M=2.14) Roomba (error bars indicate standard error). *$p < .05$

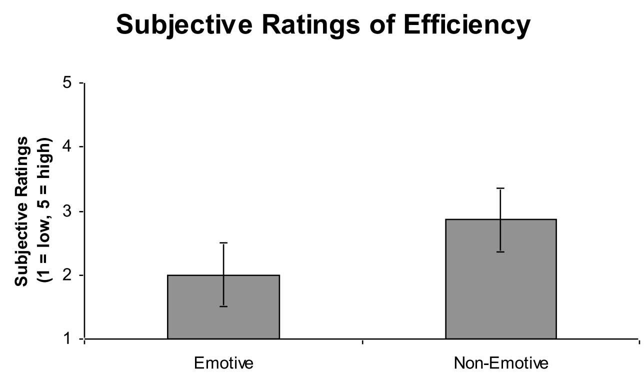

Figure 5. Subjective ratings of efficiency for emotive (M=2.00) and non-emotive (M=2.86) Roomba (error bars indicate standard error).

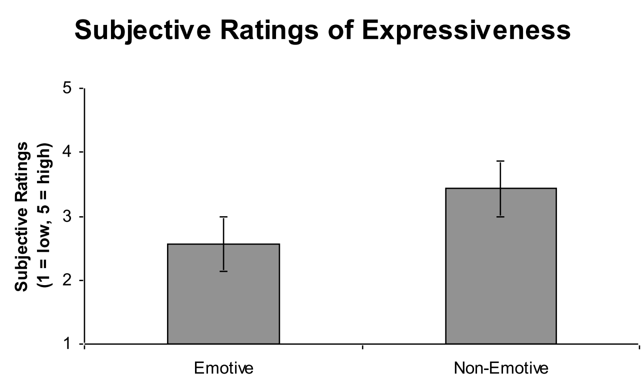

Figure 6. Subjective ratings of expressiveness for emotive (M=2.57) and non-emotive (M=3.43) Roomba (error bars indicate standard error).

Edge conditions. Participants observed the emotive Roomba respond to several edge conditions. Table 4 illustrates the participants' responses coded as the six basic emotions and neutral (please note, some responses were coded as "other" but are not represented here. The six basic emotions and neutral are displayed for ease of comparison to experiment 1). The data partially supports the experimenters' hypothesis of corresponding to the emotions identified with the edge conditions in the questionnaire from experiment 1 (refer to Table 2). More specifically, similar to experiment 1, the emotion fear was often identified in correspondence with the edge conditions 'Roomba battery running low' and 'Roomba approaches an edge'. Additionally, the edge condition 'Roomba bumps into an object' was often identified with surprise. However, there were some obvious inconsistencies when comparing this data to experiment 1. For example, more edge conditions were identified as fear (e.g., bump or stuck) and lift was often associated with anger. Finally, the Roomba's response to dirt was often identified as neutral, rather than happy.

Table 4.
Frequency of edge condition identification (n = 7).

Edge Cond.	Anger	Disgust	Fear	Happy	Sad	Surprise	Neutral
Battery Low	0	1	3	0	1	1	1
Battery Die	0	0	2	0	1	0	2
Lift	4	1	2	0	0	1	0
Bump	0	0	3	0	0	3	1
Stuck	2	1	2	0	0	0	1
Edge	0	0	4	0	0	3	1
Dirt	0	0	0	2	0	0	4

DISCUSSION & CONCLUDING REMARKS

The mixed expected and unexpected results bring about interesting observations and implications. The experimenters' hypotheses were supported by the results from experiment 1 suggesting that the Roomba is, in fact, capable of demonstrating emotional behavior. Moreover, participants fairly consistently identified emotions that they would expect the Roomba to demonstrate given the context of an edge condition.

However, the second experiment did not generally support the experimenters' hypotheses and expectations. For example, participants overwhelmingly preferred the non-emotive standard Roomba, and failed to recognize the emotive Roomba as having social characteristics. Furthermore, the demonstrations of the edge conditions coupled with emotive behavior did not generally elicit better recognition of the emotion the Roomba was attempting to display.

Given the small sample size and possible confounds of the study, the authors do not wish to suggest that the results refute the general hypothesis that there are several situations where the human owner's understanding of the Roomba's situation could be improved by allowing the Roomba to exhibit emotional behavior. Rather there are a number of recommended experimental design changes that should be applied to future work in order to more fully address this problem space.

First, the inconsistencies of the participants coupling the intended emotion with the edge conditions in experiment 2 may suggest several issues, such as a possible lack of salience, inappropriate timing, or ambiguity of the expressed emotions. For example, the experimenters noted that the emotive sounds the Roomba demonstrated during the emotion 'happiness' were unable to be heard over the vacuum. Further pilot testing and adjustments to the emotional intelligence system may eliminate some of these possible confounds.

Second, interestingly a number of the participants indicated that they thought the non-emotive Roomba was more social and enjoyable. Upon further questioning, the participants indicated that they thought the emotive Roomba was “frustrating”, “disobedient”, or “aggressive.” One participant elaborated by stating that the “Roomba was like a disobedient dog or pet”. The authors believe that this may be attributed to the high number of negative emotions associated with the edge conditions. Inducing the edge conditions and forcing the Roomba into a relatively constant negative state may have given the impression that the Roomba’s “personality” (or long-lasting emotive stance) was negative. The authors recommend future work to investigate possible edge conditions that could be associated with more positive emotions, such as happiness.

There are at least three readily apparent next steps along the path of Ollie’s development. First, entities within Ollie do not have any variety of long-term memory. The state upon which the agencies operate is transient and malleable. A good next step would be to provide both a perceptual and an episodic memory to Ollie. A perceptual memory would help with local coherence, and a long-term episodic memory would assist that process as well.

Second, metacognition is a subject studied intensely in Georgia Tech’s Design Intelligence Lab, of which two of the authors are members. Ollie’s architecture affords ready self-reflection and blame analysis. Constructing a full metacognition layer with this framework seems straightforward.

Third, the entity system of Ollie has anticipated the development of experiments in simulation theory. One of the authors is chiefly concerned with this as it relates to imitation research.

While the preliminary results from these studies are not straightforward, they do signify the complexity of creating emotive robots. While it is generally believed that emotions can improve the effectiveness of a robot, this study suggests that careful application and delivery of such emotions is crucial in promoting user acceptance. Studies, such as the current research, are vital in better understanding social robotics, and developing robots that are expressive, effective, and emotionally intelligent.

REFERENCES

Aviezer, H., Hassin, R. R., Ryan, J., Grady, C., Susskind, J., Anderson, A., Moscovitch, M., & Bentin, S. (2008). Angry, Disgusted, or Afraid? Studies on the Malleability of Emotion Perception. *Psychological Science*, *19*(7), 724 – 732.

Breazeal, C. (2003). Emotion and sociable humanoid robots. *International Journal of Human-Computer Studies*, 59(1-2):119-155.

Breazeal, C. L. (2004). *Designing Sociable Robots (Intelligent Robotics and Autonomous Agents)*. The MIT Press.

Dennett, D. True Believers. In Dennett, D. (1987). *The Intentional Stance*, MIT Press.

Edelman, G. M. (2004). *Wider than the Sky: The Phenomenal Gift of Consciousness.* Yale University Press.

Edelman, G. M. (2007). *Second Nature: Brain Science and Human Knowledge*. Yale University Press.

Ekman, P. (1992). Are there basic emotions? *Psychol Rev*, 99(3):550-553.

Francis, A.G., Jr., Mehta, M., and Ram, A. (2010) Emotional Memory and Adaptive Personalities. To appear in: Vallverdú, J. & Casacuberta, D. (Eds.) (2010). *Handbook of Research on Synthetic Emotions and Sociable Robotics: New Applications in Affective Computing and Artificial Intelligence.* Hershey, Pennsylvania: IGI Global.

Hebb, D.O. (1949). *The organization of behavior.* New York: Wiley

Hoffman, G. and Breazeal, C. (2004). Collaboration in human-robot teams. In Proc. of the AIAA 1st Intelligent Systems Technical Conference, Chicago, IL, USA, September 2004. AIAA. Johnston, O. and Thomas, F. (1995). *The Illusion of Life: Disney Animation*. Hyperion.

Minsky, M. (1988). *SOCIETY OF MIND*. Simon & Schuster.

Minsky, M. (2006). *The Emotion Machine: Commonsense Thinking, Artificial Intelligence, and the Future of the Human Mind*. Simon & Schuster.

Nass, C., Fogg, B. J., & Moon, Y. (1996). Can computers be teammates? *International Journal of Human-Computer Studies, 45*(6), 669-678.

Nass, C., & Moon, Y. (2000). Machines and mindlessness: Social responses to computers. *Journal of Social Issues, 56*(1), 81-103.

Nass, C., Moon, Y., Fogg, B. J., & Reeves, B. (1995). Can computer personalities be human personalities? *International Journal of Human-Computer Studies, 43*(2), 223-239.

Robbins, P. (2006). The Ins and Outs of Introspection. *Philosophy Compass 1 / 6* : 617-630.

Scherer, K.R. (1988). *Facets of Emotions.* Lawrence Erlbaum Associates.

Titinen, H., May, P., Reinikainen, K., and Näätänen, R.. (1994). Attentive novelty detection in humans is governed by pre-attentive sensory memory. *Nature 372*: 90-92.