Dissertation Prospectus: Developing an Awareness of Social Contingency for Social Robot Interventions

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August 2022

Abstract

The ability to coordinate one's behavior with others and, therefore, be social, demands a sensitivity to other people's responsiveness to one's own presence and behavior. Research that describe social contingencies and the human ability to detect those contingencies are typically focused on short-term interactions under controlled laboratory or clinical settings, or ultimately fail to demonstrate whether the findings generalize to naturally-occurring, real-world interactions. In other words, social contingency has traditionally been studied using abstract methods that say little about the real world and real people. Given that social robots can be a valuable tool for supporting productive social-skills interventions, I aim to develop theories for the detection and prediction of social contingency in real-world interactions. Ultimately, I apply these theories to embodied systems to optimally support users of various cognitive and technical abilities.

Keywords: social contingency, human-robot interaction, autism spectrum disorders, social-skills intervention, in-home systems

Introduction

Social interaction requires the detection of and responsiveness to each other's behavior (Coey et al., 2012; Dale et al., 2013). Detecting the social contingency between a particular behavior of one individual and the behavior of another is a complex task, and the study of social contingency detection is as elusive a concept as the study of "connectedness" or "social chemistry." Yet, the research community has made multiple attempts to explore the aspects of a social interaction that generates specific temporal patterns, whether other individuals recognize these patterns, and whether the continuity of a social interaction depends on one's ability to recognize the mutuality and contingency of these behavioral patterns. In all, the awareness of social contingency has an essential communicative purpose and its temporal dynamics contributes valuable information to each member of a social interaction and about the interaction as a whole.

The study of social contingency is especially pertinent for designing interventions for social learning disorders, such as Autism Spectrum Disorder (ASD), as these disorders are typically characterized by one's difficulty to co-regulate their behavior with that of other human beings. For example, atypical gaze behavior with others is a diagnostic hallmark of ASD and contributes to many of the reciprocal social and communicative challenges individuals with ASD face (Arnold et al., 2000; Falck-Ytter et al., 2015). As a result, individuals with ASD show reduced motivation to share attention with other (Chevallier et al., 2012). When compared to neurotypicals, individuals with ASD initiate joint attention to a lesser extent, are less sensitive to others' social gaze, and tend to avoid eye contact (Del Bianco et al., 2021; Senju & Johnson, 2009). Awareness of and detecting improvement in one's capacity to be socially contingent are evidently useful skills for humans, and therefore can be useful indicators of success when designing social-skills interventions.

In all, I aim to develop theories for the detection and prediction of social contingency in real-world interactions. Then, I will apply these theories to embodied systems to optimally support users of various cognitive and technical abilities.

Background

Several gaps currently exist in the social contingency literature. I list these gaps in the literature below and, for each, I describe the challenges that contribute to them as well as areas of future research.

1. Current findings are limited in their application to certain populations.

Prior efforts in social contingency detection traditionally aim to characterize the changing social understanding of the self and others in infants over the course of early development (Rochat, 2001). Although the capacity for social contingent behavior is assumed to have largely matured in infancy (Bigelow & Rochat, 2006; Hermans et al., 2021), little research has been done to examine whether this capacity continues to develop in adolescence and adulthood. Studies of *individual* social cognition as the main factor of interaction overlook what fundamentally constitutes a "social interaction"—that actual social interaction involves dynamic behavioral coordination between individuals. To design social-skills interventions that better addresses the needs of individuals with varying abilities at varying stages of life, we should examine social contingency longitudinally or in adulthood.

2. Existing measures describe individual, not dyadic, social cognition.

Furthermore, the prevalence of research in individual social cognition has naturally encouraged the development of assessments that describe individual social cognition during an interaction. Consequently, few, if any, measures have been developed to characterize social contingency in a given interaction. The lack of measures to describe behavioral mutuality or coordination results in inaccurate, incomplete, and difficult analyses of basic phenomena such as engagement or cooperation. An open area of research is to create definitions of social contingency and explore the relationship between these definitions and those of engagement or cooperation, for example. Moreover, the reliance on only measures for individual cognition to assess the impact of a social-skills intervention lacks metrics of social improvement and do not fully address effectiveness of an intervention. Future research should incorporate measures of socially contingent behaviors into the discussion of intervention success.

3. Most measures of coordination rely on neuroimaging techniques.

Recently, efforts to measure social contingency integrate social coordination into neuroscience, resulting an analysis of inter-brain synchronization in real-time dyadic interactions. Social neuroscience research, within the past decade, has made significant strides away from its almost exclusive focus on the individual brain as a detached interpreter of social stimuli and has focused more on the reactive and synchronous neural mechanisms involved in embodied social interaction. The interactive brain hypothesis (IBH) claims that social cognition requires causal relations between the brain and the social environment. As such, the IBH provides a useful theoretical framework for investigating the underlying neural mechanisms of social interaction (De Jaegher et al., 2016; Hirsch et al., 2018).

Neuroimaging techniques are assumed to produce objective indicators of how single within-brain subsystems mediate instantaneous and dynamic exchanges of information during live interpersonal interactions between dyads. Yet, this research assumes that measuring brain synchronization is a good surrogate for measuring behavioral social coordination. This assumption has been previously challenged because this coordination mainly reflects motor synchronization, which is not necessarily social (Hermans et al., 2021). Moreover, the findings from neuroimaging studies are based on small sample sizes (fewer than 10 dyads, Czeszumski et al., 2020) engaged in short-term interactions (less than an hour) in a laboratory or clinical setting, requiring specialized equipment and an unnatural, restricting setup (Hirsch et al., 2018).

4. Small sample sizes, short-term interactions in artificial environments

Limited sample sizes, settings, and interactions pervade social contingency research beyond the neuroscientific community. This is unsurprising because the laboratory or clinical setting provides a controlled environment in which variables of interest can be manipulated independently and their effect directly observed. Futhermore, the perceptual demands for analyzing social interactions are significant, which make examining short-term and controlled interactions an intuitive design choice for studies. Social cues—such as gaze direction or vocal intonation—are rapid, detailed, and nuanced signals embedded within a specific context or activity. For example, a slight delay in responding to a question may be interpreted as a sign of uncertainty, or the rising inflection of a single phoneme may make the difference between an eager greeting or a rhetorical question. At first glance, capturing dynamic social interaction at a behavioral level is mainly a perceptual challenge.

In order to capture social contingency behaviorally and address its inherent perceptual difficulty, the Perceptual Crossing Experiment (PCE) was developed (Auvray & Rohde, 2012; Lenay et al., 2011). The experimental framework allows researchers to examine participants' capacity for social contingency detection and responsiveness within a minimalistic virtual environment. In this environment, participants receive only haptic feedback, cannot see or hear each other, but are instructed to detect and identify the other member of their dyad. To detect and identify the other person, participants need to interact with an entity that crosses their path by moving back and forward. By reacting to an entity that crosses their process, participants establish an interaction and capture the responsiveness of the other, thus demonstrating social contingency in the interaction. Many studies rely on the PCE (a review by Deschamps et al., 2016) and, therefore, only assess behavioral coordination via a single modality (i.e., haptic feedback) in a specific interactive capacity. Although the PCE allows a controlled environment for studying social contingency at the haptic level, it is not a sufficient substitute for studying social contingency in real world interactions.

5. The potential role of social robotics for social contingency research.

Social robotics has the potential to augment efforts to define and detect social contingency in real-world, naturally-occurring interactions. As compared to the PCE and other standard methods for assessment, social robots can utilize multiple modalities for interaction such as physical interaction through embodiment, naturalistic eye and gestural movement, and speech. As a result, socially assistive robotics (SARs) has the potential to augment the current efforts of caregivers and clinicians to elicit more positive and productive outcomes in social-skills interventions (Scassellati et al., 2012). The robots envisioned by these efforts support social and cognitive growth by improving access to on-demand, personalized, socially-situated, and physically co-present interventions. Existing research on SARs as tools for social-skills training show increased engagement, improved attention regulation, and more appropriate social behavior such as joint attention and spontaneous imitation when robots are part of the interaction (Pennisi et al., 2016; Scassellati et al., 2012).

It is suggested that robots occupy a special niche on this spectrum of sociability–one end are inanimate toys that do not elicit social behaviors whatsoever, and other the other end are animate social beings which can be a source of overwhelming confusion and distress to certain individuals, such as in ASD. The ability to modulate where on the spectrum of sociability a SAR occupies by adjusting its interactive components means that robots can be valuable tools for understanding human behavior. Furthermore, robot-assisted interventions in which a SAR adjusts its behavior according to the behavior and needs of its users can provide valuable diagnostic and therapeutic insights. For example, in ASD research, this emerging "second-person" or interactive approach to social cognition presents a more promising framework for studying ASD than classical approaches which focus on mentalizing capacities in detached, observer-based arrangements.

However, existing studies on the impact of SARs focus mainly on short-term interactions under controlled settings, fail to demonstrate learning that generalizes to human-directed actions, and are designed to study improvements in individual social cognition. Most of these gaps in the literature can be attributed to challenges in the development and deployment of social robots. Although we have made substantial advances in machine perception in the last decade, especially in object recognition, action recognition, and human gaze analysis, we still lack systems that operate under the diverse natural conditions and real-world time constraints that social interactions demand. Next-generation systems will need to richly mix elements from multiple input modalities and combine these perceptual systems with predictive models of social intention to more fully capture the rich, dynamic nature of social interactions.

Thesis

The objective of this research is to develop theories for the detection and prediction of social contingency in real-world dyadic interactions. Ultimately, I apply these theories to embodied systems to design robot-assisted social-skills interventions that optimally support users of various cognitive and technical abilities.

Challenges in social robotics research that will need to be addressed to explore human social contingency in my research include the following:

R1 Building systems that are robust and autonomous for long-term interactions with users of various cognitive and technical abilities

R2 Automated measures of performance in the dynamic, unconstrained environment such as the home demand complex sensing. In light of this, I will develop methods of detection that are computationally efficient. One approach is to use machine learning techniques to determine which features of the environment, interaction, and social context are the most relevant to social contingency. Then, I will be able to develop pipelines for processing and utilizing those features in near real-time. Another approach involves examining what social information can be gained from sensory data other than the conventional methods of vision and speech analysis; computer vision can be computationally expensive to process, and human speech is usually specific to culture and language. Little is known about what social information can be gained from the low-level features of audio or haptic data, for example.

R3 An understanding of people's activity and the social context can improve a system's decision-making and behaviors. In this thrust of my research, I will apply the aforementioned measures of social behavior to design robot-assisted social-skills interventions.

R4 Next, a system's awareness of users' socially contingent behaviors can result in better evaluations of intervention efficacy. Current measures of intervention success describe individual social cognition and are collected manually by a clinician or the experimenter at discrete time points during the intervention or after the completion of an intervention study. The work in the above lines of research provide for the automatic, near real-time assessment of users' social behavior during interactions with reactive and skill-aware robot systems,

Gaps in the current methodologies of social contingency research that will be addressed in my research are as follows.

M1 As previously mentioned, existing research in social contingency focus on infants and the changes in social understanding throughout early development. To design social-skills interventions that better addresses the needs of individuals with varying abilities at varying stages of life, I plan to investigate social contingency longitudinally or in adulthood, and for users with atypical social development and disorders.

M2 One thrust of my research is to examine patterns of attentional shifts in people. The shifting of attention during an interaction is needed to allocate finite attentional resources to more efficiently process information from various stimuli. Understanding how people allocate their finite attentional resources during an interaction is a prerequisite for better understanding social contingency detection.

M3 Many standardized assessments describe individual social cognition during an interaction and overlook important aspects of dyadic social contingency. The study of engagement and cooperation, for example, can benefit from measures that describe behavioral coordination and mutuality. Therefore, I intend to develop and incorporate measures of socially contingent behaviors to expand current methods of assessing the success of social-skills interventions.

M4 One objective of my research in designing productive robot-assisted social-skills interventions is to produce clinically meaningful results. Two approaches I can take to achieve this are: (1) *diagnostically*, in that I compare changes made in typically developing individuals versus neurodiverse individuals as a result of the intervention in order to expand our understanding of known social disorders in terms of social contingent behaviors; and (2) *therapeutically* by investigating (a) the amount of time and interactive components needed to adjust to the initial novelty of the system, (b) the short-term effects of interacting with the system over the course of the intervention, and (c) how quickly those effects deteriorate over time in the absence of continued support from the intervention.

The following is a list of my past, ongoing, and future work that support this thesis. This also includes a timeline for collecting data, developing systems, and submitting publications that will answer the research directions outlined above. While the specific venues I submit publications to are subject to change based on exact study design and results, this is the general timeline I aim to follow to complete the research for my dissertation.

P1 Exploring the neural mechanisms of dyadic social communication using human-robot interaction (*unpublished*), March 2020.

Addresses **M3**

Our approach to studying the mechanisms of dyadic social communication using human-robot interaction is predicated on the idea that artificial agents can be better perceived as social by designing them in a way that activates areas in the human brain involved in social-cognitive processing (Cook et al., 2012; Cross et al., 2019; Wiese et al., 2017). We presented a top-down approach to social robotics development, where a social robot are designed with the mind of eliciting similar neural feedback in humans such as that in human-human interactions. Another contribution of this study is the assessment of whether the IBH is applicable to artificial agents.

Keywords: social robotics, neuroscience, dyadic social interaction

P2 Challenges deploying robots during a pandemic: an effort to fight social isolation among children (Tsoi et al., 2021).

Addresses **R1**

Although robots are currently used to combat the effects of the COVID-19 pandemic in areas of clinical care, logistics, and surveillance, their potential to mitigate the implications of social distancing remains understudied [29]. To advance our understanding of this potential and in an attempt to mitigate the social consequences of the current pandemic, we explored one way in which robots can help children with social isolation. We developed a robot teleoperation system, called VectorConnect, for elementary school-aged children to engage in physical play while being geographically separated. We discuss the challenges that we encountered through our deployment as well as the lessons that we learned to facilitate effort to innovate in times of global crises.

Keywords: long-term in-home social robot deployments, social isolation, children

P3 A social robot for improving interruptions tolerance and employability in adults with ASD (Ramnauth et al., 2022).

Addresses **R1**, **R2**, **M1**, and **M2**. Further analyses of the current dataset can address **R3**, **R4**, and **M4**, as well as **M2** in more detail.

Individuals with Autism Spectrum Disorders (ASD) exhibit social skill deficits such as difficulties with reciprocal social interaction, interpersonal communication, and insistence on behavioral and environmental sameness. Supporting work reveals that one barrier to employment for adults with ASD is dealing with workplace interruptions. In this paper, we present our design and evaluations of an in-home autonomous robot system that aims to improve users' tolerance to interruptions. The Interruptions Skills Training and Assessment Robot (ISTAR) allows adults with ASD to practice handling interruptions to improve their employability. ISTAR is evaluated by surveys of employers and adults with ASD, and a week-long study in the homes of adults with ASD. Results show that users enjoy training with ISTAR, improve their ability to handle various work-relevant interruptions, and view the system as a valuable tool for improving their employment prospects. Ultimately, this work demonstrates that a robot-assisted intervention can be an effective tool for improving how adults with ASD allocate their attention in the presence of interruptions.

Keywords: long-term in-home deployment, robot-assisted social-skills intervention, attention shifting, adults with ASD

P4 Detecting physical social presence through sound for social robots (*pending publication* in the Journal of Human-Robot Interaction), August 2022.

Addresses **R1**, **R2**, and **R3**.

Audio information can provide social robots valuable information about its environment, its users' activity, and its social context. This study attempts to solve the challenge of detecting physical social presence through sound, which classifies audio from in-home environments as containing either natural conversation from co-located users or media playing from electronic sources that does not require a social response from a user, such as television shows. Social robots that are able to solve this problem can use this information to help them in making decisions, such as determining when and how to appropriately engage human users. We compiled a dataset from a variety of acoustic environments which contained either natural or media audio. Using this dataset, we performed an experimental evaluation on a range of traditional machine learning classifiers, and assessed the classifiers' abilities to generalize to new recordings, rooms, speakers, and microphone distances. We performed experiments on "in-the-wild", natural audio, including video calls and dinner conversations. We conclude that our C-Support Vector Classification (SVC) algorithm outperformed other classifiers. Finally, we present a classification pipeline that in-home systems can utilize, and offer a possible use case within the context of engaging with a user.

Keywords: in-home interactive systems, audio analysis, human-centered computing, feature extraction, machine-learning

P5 Improving tolerance to interruptions through training (*ongoing*), expected submission to the *Proceedings of the National Academy of Sciences (PNAS)* in September 2022.

Addresses **M1** and **M2**. A future extension of this project can address **M4** by expanding the participant pool to include neurodiverse individuals.

In light of the results of the ISTAR study, we examine which factors make training to reduce the disruptiveness of interruptions effective. Our study examines which training conditions (type of task, type of interruption, the co-occurrence of task and interruptions, and novelty of interruption or task during training) support more error-free and quicker recovery from interruptions. In our 2 x 2 x 2 x 2 mixed-repeated factorial design, participants across 16 training conditions train to improve their performance in strategy, memory, numerical calculation, and semantic processing tasks. We find that improvement may naturally arise from repeated exposure to the task. However, experiencing the co-occurrence of the task with novel interruptions can result in more significant improvement. Furthermore, particular task-interruption pairings demonstrate to be more effective than other task-interruption pairings. Ultimately, we discuss the factors that make interruptions more or less disruptive and provide recommendations for training to reduce the disruptiveness of interruptions.

Keywords: interruptions, training, memory, attention, learning

P6 Gaze behavior during a long-term, in-home, social robot intervention for children with ASD (*ongoing*), expected submission to the *Journal of Autism and Developmental Disorders (JADD)* in October 2022.

Addresses **R1**, **R2**, **R3**, **M1**, **M2**, **M3**, and **M4**.

Atypical gaze behavior is a diagnostic hallmark of ASD and contributes to many of the social and communicative challenges individuals with ASD face. This study reports directly assessed improvements in social skills in children with ASD following an in-home one-month intervention conducted by an autonomous, socially assistive robot (Scassellati et al., 2018). The robot-assisted intervention involved triadic opportunities for shared experiences among the robot, the child, and the caregiver. We explore several aspects of gaze behavior in caregivers and children with ASD to evaluate the contribution of the social robot in the intervention and to better understand gaze behavior in ASD. We ultimately demonstrate that the robot-assisted intervention improved various aspects of gaze behavior in children with ASD, that there is a marked difference in when children with ASD improve, and diagnostic measures can be good predictors of long-term gaze behavior of both the caregivers and children with ASD.

Keywords: ASD, social gaze, long-term in-home social robot deployment, robot-assisted intervention

P7 Accuracy of existing gaze detection methods on individuals with ASD (*future*, may be incorporated into P6), expected submission to a computer vision journal such as the *IEEE Transactions on Pattern Analysis and Machine Intelligence* or a social robotics venue such as HRI, JHRI, or RO-MAN in October 2022.

Addresses **R1**, **R2**, **R3**, **M1**, **M2**, **M3**, and **M4**.

Many gaze detection models are trained on neurotypical adults. However, there are very few datasets that represent gaze behavior in children or neurodiverse individuals. We initially examine the applicability of existing models for these unique populations. Identifying areas in which existing models (e.g., OpenFace, OpenCV) do not accurately represent behaviors in these populations can grant insights for building systems that mitigate these possible fallacies or encourage datasets that better represent different populations. We then apply our findings to analyze gaze behavior in children with ASD during an in-home month-long robot-assisted intervention.

Relevant keywords: ASD, social gaze, detection accuracy, long-term in-home social robot deployment, robot-assisted intervention

P8 Speed of social contingency detection in self and others (*future*), expected submission to a general sciences venue such as PNAS and/or a robotics venue such as HRI, RO-MAN, or CHI in May 2023.

Addresses **R2**, **M1**, **M2**, and **M3**. A future extension incorporating a robot system as one of the members of the dyad will address **R1**, **R2**, **R3**, **M1**, **M3**, and **M4**.

This study presents various situations which have the potential to be socially interactive. We will examine how quickly an individual recognizes another individual is social responsive to their behaviors by various definitions of responsiveness (e.g., gaze behavior, head pose orientation). We also examine how quickly an individual recognizes that two individuals are interacting with each other.

Keywords: social awareness, social contingency detection, dyadic interaction

P9 Characteristics of speech behavior that signals social contingency for social robots (*future*), expected paper submission to a robotics venue such as RO-MAN or HRI in September 2023.

Addresses **R2**, **M1** and **M3**. A future extension of this study will address **R3**, **R4**, and **M4**.

The objective of this study is to investigate whether low-level features in an individual's speech, as well as the structural composition of an interaction between two social agents, can signal the presence or lack of social contingency in speech. A preliminary study conducted in May 2021 investigates which low-level features play the largest roles in dyadic engagement modeling. Next, we used an engagement model to measure how often individuals appear to be engaged in a conversation, and whether coupling this measurement with silence between utterances can give any insight towards the concept of social contingency. In this paper, we presented a Random Forest Classifier that can classify engagement from a spoken utterance with 83% accuracy by extracting a combination of low-level audio features. Using an Analysis of Variance measure, we determined ten audio features that that contribute the most to an engagement or disengagement classification. These measurements were visualized against proposed measures of social contingency such as the average duration of each silent period, the increase or decrease of silence over the course of a conversation, and the confidence of the engagement model. The results suggest that, although further investigation is needed, these simple structural features together can signal whether two individuals are socially contingent.

Keywords: audio analysis, engagement, social contingency detection, feature-extraction, machine learning

Altogether, this research involves a substantial amount of data collection involving children and neurodiverse individuals as well as the development of computational models, system development, data analysis, and paper writing. Participant recruitment and data collection will likely be collected in Connecticut, New York, or online. All materials and associated work to be completed (e.g., system development, study data and analysis) will be stored in AKW 500, the main lab room of the Yale Social Robotics Lab.

Committee

A dissertation committee consists of three computer science faculty at Yale, including one primary advisor, as well as one external faculty member from another institution. Below is my proposed committee of readers according to their relevant research interests.

- Internal Commitee Members:
  - Dr. Brian Scassellati (primary advisor), Yale Social Robotics Lab
    Related interests: HRI, artificial intelligence, cognitive modeling
  - Dr. Marynel Vázquez (*tentative*), Yale Interactive Machines Group
    Related interests: HRI, multi-agent interaction, artificial intelligence
  - Dr. Aaron Dollar (*tentative*), Yale Grasping & Manipulation, Rehabilitation Robotics, and Biomechanics (GRAB) Lab
    Related interests: robotics, machine and mechanism design, rehabilitation and assistive devices
- External Committee Member: Dr. Maja Matarić (*tentative*) at the University of Southern California Robotics and Autonomous Systems Center
  Related interests: social robotics, assistive technologies, HRI

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