Cognition 141 (2015) 73–86

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Signaling equilibria in sensorimotor interactions

Felix Leibfried [a,b,c,*], Jordi Grau-Moya [a,b,c], Daniel A. Braun [a,b]

[a] Max Planck Institute for Biological Cybernetics, Tübingen, Germany
[b] Max Planck Institute for Intelligent Systems, Tübingen, Germany
[c] Graduate Training Centre of Neuroscience, Tübingen, Germany

ARTICLE INFO

Article history:
Received 2 July 2014
Revised 2 March 2015
Accepted 15 March 2015
Available online 14 May 2015

Keywords:
Sensorimotor communication
Joint action
Decision theory
Game theory
Signaling game
Perfect Bayesian Nash equilibria

ABSTRACT

Although complex forms of communication like human language are often assumed to have evolved out of more simple forms of sensorimotor signaling, less attention has been devoted to investigate the latter. Here, we study communicative sensorimotor behavior of humans in a two-person joint motor task where each player controls one dimension of a planar motion. We designed this joint task as a game where one player (the sender) possesses private information about a hidden target the other player (the receiver) wants to know about, and where the sender's actions are costly signals that influence the receiver's control strategy. We developed a game-theoretic model within the framework of signaling games to investigate whether subjects' behavior could be adequately described by the corresponding equilibrium solutions. The model predicts both separating and pooling equilibria, in which signaling does and does not occur respectively. We observed both kinds of equilibria in subjects and found that, in line with model predictions, the propensity of signaling decreased with increasing signaling costs and decreasing uncertainty on the part of the receiver. Our study demonstrates that signaling games, which have previously been applied to economic decision-making and animal communication, provide a framework for human signaling behavior arising during sensorimotor interactions in continuous and dynamic environments.

1. Introduction

Signaling is a ubiquitous phenomenon in animal and human societies. Examples of signaling in the animal kingdom include color warnings, odors, pheromones, and sounds that inform about inedibility, the ability to defend a resource, or the general fitness of an animal (Maynard Smith & Harper, 2003). In humans, the most advanced form of signaling is undoubtedly language, but there are also non-verbal forms of signaling that rely on sensorimotor interactions (Obhi & Sebanz, 2011; Pezzulo, Donnarumma, & Dindo, 2013; Sacheli, Tidoni, Pavone, Aglioti, & Candidi, 2013; Sebanz, Bekkering, & Knoblich, 2006), including facial expressions (Ekman, Sorenson, & Friesen, 1969), interpersonal distance and body orientation (Remland, Jones, & Brinkman, 1995). Studying sensorimotor signaling is not at last interesting, because language is often thought to have evolved out of these more "primitive" forms of signaling (Gallese & Lakoff, 2005).

Sensorimotor interactions can be studied both from a dynamical systems (Kelso, 1995) or a decision-theoretic (Landy & Wolpert, 2012) point of view. In particular, game-theoretic models have been used under the latter point of view to study sensorimotor interactions between multiple players that optimize motor effort (Braun, Ortega, & Wolpert, 2009, 2011). In Braun et al. (2009), pairs of players were coupled by force fields, where each player experienced a different force field that depended on both

* Corresponding author at: Max Planck Institute for Biological Cybernetics, Spemannstr. 38, 72076 Tübingen, Germany.
E-mail address: felix.leibfried@tuebingen.mpg.de (F. Leibfried).

http://dx.doi.org/10.1016/j.cognition.2015.03.008
0010-0277/

players' motion. The force fields could thus be used to encode player-specific payoffs, indicating costs or rewards in strategic interactions like the Prisoners' Dilemma. In such coupled force landscapes, the players converged to movements that could be described by game-theoretic Nash equilibria, that is combinations of strategies where any unilateral deviation of a player from her strategy would not result in a higher payoff for that player. Players could also co-adapt in single movement trials to converge to a Nash equilibrium if the force landscape encoded multiple equilibria (Braun, Ortega, & Wolpert, 2011). However, players had no private information in these games and therefore, there was no incentive for signaling.

Signaling between multiple players becomes an issue when one player possesses private information the other player is interested in, and when this player can trade her private information to persuade the other player to act in her favor. This scenario is studied in signaling games (Cho & Kreps, 1987). A paradigmatic example of a signaling game is the *job market signaling game* (Spence, 1973) between a job applicant (the *sender*) and a future employer (the *receiver*)—compare Fig. 1. Crucially, the future employer cannot directly inspect the applicant's working skills (the *type* or private information), but has to rely on the applicant's *signal*, for example previous educational certificates. The signal is expensive for the applicant, as higher educational certification is thought to be more difficult to acquire for applicants with low working skills. While the applicant's goal is to receive a payment that is as high as possible, the employer might want to match the payment (the *action*) to the applicant's skill level. Previously, the framework of signaling games has been applied to model economic decision-making in discrete, non-dynamic environments (Banks, Camerer, & Porter, 1994; Drouvelis, Müller, & Possajennikov, 2012; Potters & van Winden, 1996). In these experiments, subjects were asked to inspect payoff matrices to make decisions between two or three different signals or actions in order to maximize their expected monetary reward. Outcomes were then revealed once both players had made their separate choices in a sequential fashion.

Here, we are interested in a game-theoretic study of sensorimotor signaling that is characterized by three features. First, we use continuous signal, action and private information spaces. Second, there are dynamic interactions between signal and action rather than static and strictly consecutive interactions as in the job market signaling game. Third, instead of monetary rewards, payoffs are given in terms of color and distance cues. These three features are typical for sensorimotor interactions between humans and can be modeled as continuous two-person sensorimotor games (Braun et al., 2009, 2011). In this study, we investigate for the first time how humans behave in such games in the presence of private information. The game is played by a sender and a receiver that have partially conflicting goals in a joint control task, where each player controls one dimension of a two-dimensional movement. The sender has private information about a target location that the receiver aims to hit, while the receiver has control over the dimension that most strongly affects the sender's reward. We investigate how signaling is modulated in such a game by manipulating the signaling cost and the variability of the private information. We compare human behavior to (Perfect) Bayesian Nash equilibria predicted by signaling game theory. In particular, the predictions lead to the hypothesis that the propensity for signaling should increase with decreasing signaling costs and with increasing variability of the private information. We find these predictions confirmed in our task.

2. Materials and methods

2.1. Participants

Nine female and eleven male participants were recruited from the student population of the University of Tübingen. The study was approved by the ethics

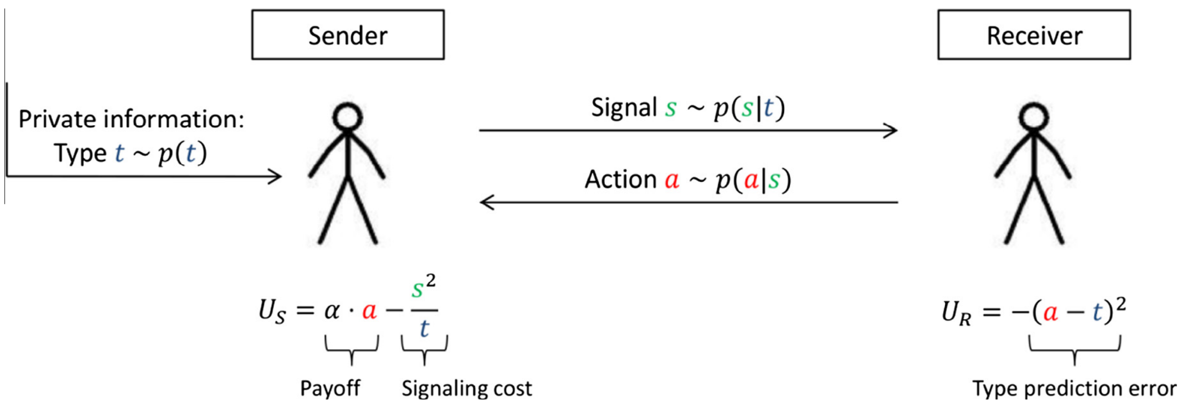

Fig. 1. Signaling game. The sender possesses private information t sampled from a type distribution $p(t)$. Depending on the type t, she decides to send a costly signal s to the receiver according to her strategy $p(s|t)$ which is a conditional probability distribution. The receiver answers the signal s with an action a according to her own strategy $p(a|s)$. Both players have different aims described by their utility functions U_S and U_R. The receiver intends to choose an action that matches the sender's type whereas the sender wants to receive a high payoff, while avoiding signaling cost. For large types, the same signal is cheaper than for low types (assuming strictly positive types). The parameter α is a scaling factor for the sender's payoff.