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An Agent Model for Computational Analysis of Mirroring Dysfunctioning in Autism Spectrum Disorders

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Abstract. Persons with an Autism Spectrum Disorder (ASD) may show certain types of deviations in social functioning. Since the discovery of mirror neuron systems and their role in social functioning, it has been suggested that ASD-related behaviours may be caused by certain types of malfunctioning of mirror neuron systems. This paper presents an approach to explore such possible relationships more systematically. As a basis it takes an agent model incorporating a mirror neuron system. This is used for functional computational analysis of the different types of malfunctioning of a mirror neuron system that can be distinguished, and to which types of deviations in social functioning these types of malfunctioning can be related.

Keywords: agent model, analysis, mirror neuron systems, autism spectrum disorder.

1 Introduction

Autism is a developmental disorder showing a wide range of (gradual) differences in functioning across patient populations. The major features that characterize autistic persons are deficits in social interaction, but also abnormalities in language within a social context and repetitive and stereotyped patterns of behavior are seen. Some characteristics can be observed in all autistic persons, but it is very rare that in one person all kinds of autism-related behavior are found. Different persons with some form of autism may feature different ranges of behaviors. Therefore nowadays the term Autism Spectrum Disorder (ASD) is used rather than autism. There seem to be no strict boundaries in the spectrum of autism. It is assumed that ASD may be caused by a number of neurological factors responsible for the specific type of ASD-related behaviours shown by a person. Since the discovery of mirror neuron systems and their role in social functioning, it has been assumed that in some way ASD relates to malfunctioning of the person's mirror neuron system; e.g. [16], [20]. Given the wide variety of deviant behaviours observed in different persons with ASD, a natural step then is to analyse functionally what types of malfunctioning of a mirror neuron system can be distinguished, and to explore how each of these types of malfunctioning relates to which types of deviant behaviours. To describe an agent-based model for such a computational analysis is the main focus of the current paper.

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A large amount of publications is available describing the behavior of persons with ASD; e.g., [10], [16], [19], [20]. There is no unique physical appearance that shows that someone has ASD. It is seen in persons of all ages and in different ranges within a broad spectrum; it is universal and timeless. The major characteristics concern deficits in social interaction. Also difficulties and a shortage in language acquisition, the tendency towards repetition of actions and narrowed focus may occur. In most cases, persons with ASD are not mentally disabled. Examples of possible characteristics found are reduced forms of self-other differentiation, empathy, imitation, eye contact, facial expression, gestures, shared intention and attention, or strong concentration on or occupation with a subject. Pioneers in research in autistic phenomena were Leo Kanner [17] and Hans Asperger [1]. They both came up with detailed case studies and made an attempt to give an explanation. The term 'autistic' was originally used by the psychiatrist Eugen Bleuler, to describe a particular case of schizophrenia, which narrows the view of the patient in an immense way; see also [3]. The main difference between the papers is that Asperger's descriptions and definitions of the disorder are broader than Kanner's view on it.

The presented approach is based on the assumption that to obtain a solid basis for a computational analysis: (1) an agent model incorporating the functionality of mirror neuron systems is designed, allowing modifications to model certain types of malfunctioning, and (2) this agent model is formally specified in an executable form to obtain the possibility to exploit computational formal analysis as a means to explore which behaviours may result from such an agent model and modified variants to model types of malfunctioning of the agent's mirroring system. With this agent model incorporating a mirror neuron system as a basis (presented in Section 2). In Section 3 different modifications of the agent model to model different types of malfunctioning are explored, and it is analysed which types of deviant social behaviour emerge from these types of malfunctioning. Section 4 is a discussion.

2 An Agent Model with a Mirror Neuron System as a Basis

Within a person's neurological processes, sensory representations of stimuli usually lead to preparations for responses. Recent neurological findings more and more reveal that socalled 'preparation' or premotor neurons have multiple functions; preparing for an action that actually is to be executed is only one of these functions. Sometimes, an action is prepared, but execution of the action is not taking place. For example, preparation of actions may play a role in interpreting an observation of somebody else performing an action, by internally simulating that action, or in imagining the action and its consequences; e.g., [15], [14], [16]. In these cases, actual execution of the prepared action is prevented. Without altering any body state, activation of preparation states can lead to further mental processing via an *as-if body loop* [7], [8] from preparation state to emotions felt by sensory representation of body states associated to the (expected) outcome of the prepared action. For the agent model, the following internal causal chain for a stimulus s is assumed; see [7], [8]:

Sensory representation of s → preparation for response → sensory representation of body state

This causal chain is extended to a recursive loop by assuming that the preparation for the response is also affected by the level of feeling the emotion associated to the expected outcome of the response:

sensory representation of body state $\rightarrow$ preparation for response

Thus the obtained agent model is based on reciprocal causation relations between emotions felt and preparations for responses. Within the agent model presented here, states are assigned a quantitative (activation) level or gradation. The positive feedback loops between preparation states for responses and their associated body states, and the sensory representations of expected outcomes are triggered by a sensory representation of a stimulus and converge to a certain level of feeling and preparation.

Apparently, activation of preparation neurons by itself has no unambiguous meaning; it is strongly context-dependent. Suitable forms of context can be represented at the neurological level based on what are called *supermirror neurons* [14, pp. 196-203], [18]; see also [5]. These are neurons which were found to have a function in control (allowing or suppressing) action execution after preparation has taken place. In single cell recording experiments with epileptic patients [18], cells were found that are active when the person prepares an own action to be executed, but shut down when the action is only observed, suggesting that these cells may be involved in the distinction between a preparation state to be used for execution, and a preparation state generated to interpret an observed action. In [14, pp. 201-202] it is also described that as part of this context representation, certain cells are sensitive to a specific person, so that in the case of an observed action, this action can be attributed to the person that was observed. Within the agent model presented in this section, the functions of super mirror neurons have been incorporated as focus states, generated by processing of available (sensory) context information. For the case modeled, this focus can refer to the person her or himself, or to an observed person.

To formalise the agent model in an executable manner, the hybrid dynamic modeling language LEADSTO has been used; cf. [4]. Within LEADSTO the dynamic property or temporal relation $a \twoheadrightarrow_D b$ denotes that when a state property a occurs, then after a certain time delay (which for each relation instance can be specified as any positive real number D), state property b will occur. Below, this D will be taken as the time step Δt, and usually not be mentioned explicitly. Both logical and quantitative calculations can be specified, and a software environment is available to support specification and simulation. The modeled agent receives input from the external world, for example, another agent is sensed (see also Fig. 1). Not all signals from the external world come in with the same level, modelled by having a sensor state of certain strength. The sensor states, in their turn, will lead to sensory representations. Sensory representations lead to a state called *supermirroring state* and to a specific motor *preparation state*. The supermirroring state provides a focus state for regulation and control, it also supports self-other distinction. In the scenario used as illustration, it is decisive in whether a prepared action is actually executed by the observing agent, or a communication to the observed agent is performed reflecting that it is understood what the other agent is feeling. Note that the internal process modelled is not a linear chain of events, but cyclic: the preparation state of the agent is updated constantly in a cyclic process involving both a body loop and an internal as-if body loop (via the connections labeled with w_6 and w_7). All updates of states take place in parallel.

Capitals in the agent model are variables (universally quantified), lower case letters specific instantiations. All strengths are represented by values between *0* and *1*. A capital *V* with or without subscripts indicates a *real number* between *0* and *1*. The variable S reflects that it is of the sort *signal* and B of the sort that concerns the agent's *body state*. What is outside the dotted lining is not a part of the internal process of the agent. The first two sensor states (sensor_state(A,V) and sensor_state(S,V)) are possibly coming from a single source in the external source, but are not further specified: their specific forms are not relevant for the processes captured in this agent model. A more detailed description will follow below. For each of the dynamic properties an informal and formal explanation is given.

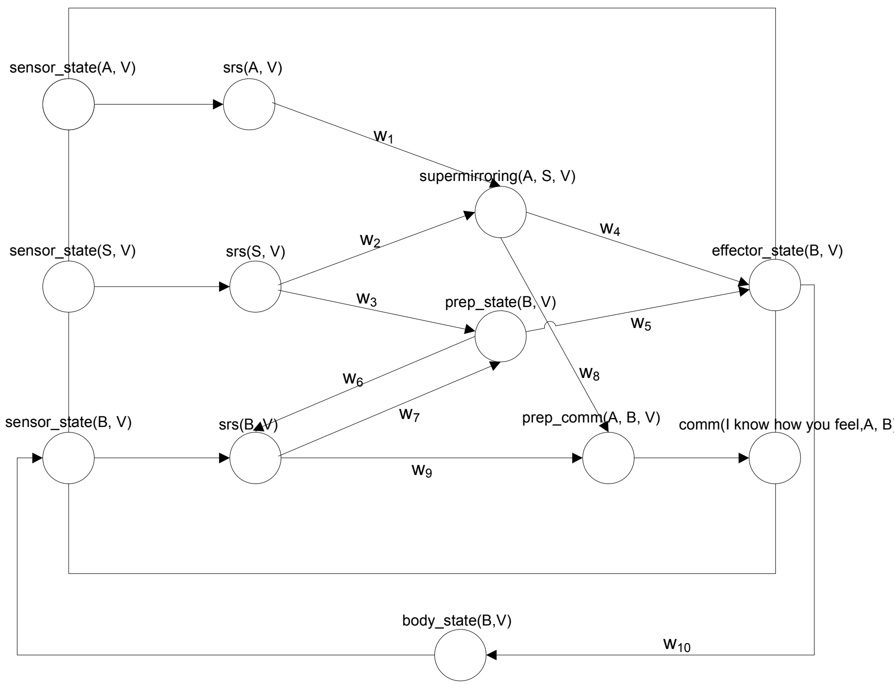

Fig. 1. Overview of the agent model

Dynamic Property 1 Generating a sensory representation for another agent

If the presence of another agent A is sensed with a certain strength *V*,
then a sensory representation of A will occur with level *V*.

sensor_state(A,V) ↠ srs(A,V)

Dynamic Property 2 Generating a sensory representation for a property of the world

If a sensor state for S is present with a certain strength *V*,
then a sensory representation of S will occur with strength *V*.

sensor_state(S,V) ↠ srs(S,V)

Super mirroring controls whether an action is to be performed (self-other distinction).

Dynamic Property 3 Super mirroring

If a sensory representation of another agent A occurs with a certain strength V_1,
and a sensory representation of any world state property S occurs with certain strength V_2,
then supermirroring for A and S will take place, with strength $f(w_1V_1, ow_2V_2)$.

srs(A,V_1) & srs(S,V) ↠ supermirroring(A, S, f(w_1V_1, ow_2V_2))

If a sensory representation of state property instance s occurs with certain strength V,
then supermirroring for self will take place, with strength V.

srs(s,V) ↠ supermirroring(self, s, sw_2V)

Here w_1 and ow_2 are the strengths of the connections from, respectively, the sensory representation of the other agent and the sensory representation of the observed action (stimulus) to the super mirroring state, and sw_2 the strength of the connection from the sensory representation of the stimulus to the super mirroring state for the case of self. These weights are in the normal situation set to value *1*. By altering these connections, different output may show in the simulations. This is interesting when validating theories about dysfunctioning in some point of the process in persons with ASD. The function $f(w_1V_1, ow_2V_2)$ is a combination function, mapping values from the interval [*0, 1*] onto values in the same interval. It can be calculated, for example, as $f(w_1V_1, ow_2V_2) = w_1V_1 + ow_2V_2 - w_1V_1\, ow_2V_2$, or by a logistic threshold function $f(w_1V_1, ow_2V_2) = 1/(1+ e^{-\sigma(w_1V_1 + ow_2V_2 - \tau)})$, with σ a steepness and τ a threshold value.

Dynamic Property 4 Preparing for motor execution

If sensory representation occurs of s_1 (movement/action) in the world with level V_1,
and the preparation for body state b_1 has level V_2
then the preparation state for body state b1 will have level $f(V_1, w_3V_2)$.

srs(b_1,V_1) & srs(s_1,V_2) ↠ prep_state(b_1, f(V_1, w_3V_2))

Not every signal S that comes from the external world and which has generated a sensory representation will have a match in the sense that the body of the agent will prepare for an action. This specificity is seen in the rule, because signal s_1 will generate body state b_1, whereas any signal s_2 will not generate b_1, but maybe some b_2. These are no universal quantified variables, which are written with capital letters in this description. As earlier, also here a connection strength is given. The weight w_3 is the relation between the sensory representation of s_1 and the preparation state for b_1. Note that when a representation is not present, the value *0* is attributed to it.

Dynamic Property 5 Generating an updated sensory representation

If the preparation state for body state B has level V_1
and the sensor state for body state B has level V_2
then a sensory representation for body state B will be generated with level $f(V_1,V_2)$.

prep_state(B, V_1) & sensor_state(B, V_2) ↠ srs(B, f(V_1,V_2))

The state of the body and the preparation states are important in order to obtain a feeling; cf. Damasio (1999). The changes in the body will change the somatosensory system. In this way the altered body state produces the feeling. The earlier mentioned *body loop* (from preparation via execution to altered body state, and via sensing thia body state to sensory representation) and *as if body loop* (direct connection from preparation to sensory representation) are combined in this part of the agent model.

Dynamic Property 6 Generating action execution

If supermirroring for self and s occurs with certain strength V_1.
and preparation of motor execution of body state b_1 occurs with strength V_2
then motor execution of body state b_1 will take place with level $f(w_4V_1, w_5V_2)$.
supermirroring(self, s, V_1) & prep_state(b_1, V_2) ↠ effector_state(b_1, f(w_4V_1, w_5V_2))

The value for the effector state is based on connection strengths from super mirroring to effector state (w_4) and from preparation state to effector state (w_5).

Dynamic Property 7 From effector state to body state

If the effector state for body state B occurs with level V,
then body state B will have level V.
effector_state(B, V) ↠ body_state(B, V)

When the agent performs an action, this generates a new body state of the agent.

Dynamic Property 8 Generating a sensor state for a body state

If a body state B is sensed with strength V,
then a sensor state body state B with the same level V will be generated.
body_state(B, V) ↠ sensor_state(B, V)

Dynamic Property 9 Generating a preparation for communication

If there is a sensory representation of body state B with level V_1,
and supermirroring indicating world state S and agent A occurs with level V_2,
then preparation of communication to A about B will occur.with level $f(w_6V_1, w_7V_2)$
srs(B, V_1) & supermirroring(A, S, V_2) ↠ prep_communication(A, B, f(w_6V_1, w_7V_2))

Also here, weights are used for connections between srs(B,V) and prep_communication(B, V) (w_6) and between supermirroring(S, V) and prep_communication(B, V) (w_7).

Dynamic Property 10 Communication

If the preparation of a communication to A about B occurs with value V.
then the agent will communicate 'I know how you feel B', to A with V as value.
prep_communication(A, B, V) ↠ communication(A, I know how you feel, B, V)

The communication that the agent knows what an observed agent feels is based upon feeling the same body state. After the observer gained the representation of the same body state, this can generate the feeling associated with it, and this is communicated.

3 Functional Analysis and Simulation Based on the Agent Model

To test the feasibility of the approach, the agent model described above was used as a basis for a functional analysis, also involving a number of simulations. The connection strengths w_1, sw_2, ow_2, w_3, w_4, w_5, w_6, w_7, w_8, w_9 and w_{10} which are parameters in the agent model, were systematically varied over the interval [0, 1], to inspect what the effects on the agent's functioning are. In the simulations, the state properties progress over time. Every delay in a temporal property corresponds to one time point in a simulation run. An example trace for normal functioning is shown in Fig. 2. The dark lines in the upper part of this picture indicate the time intervals for

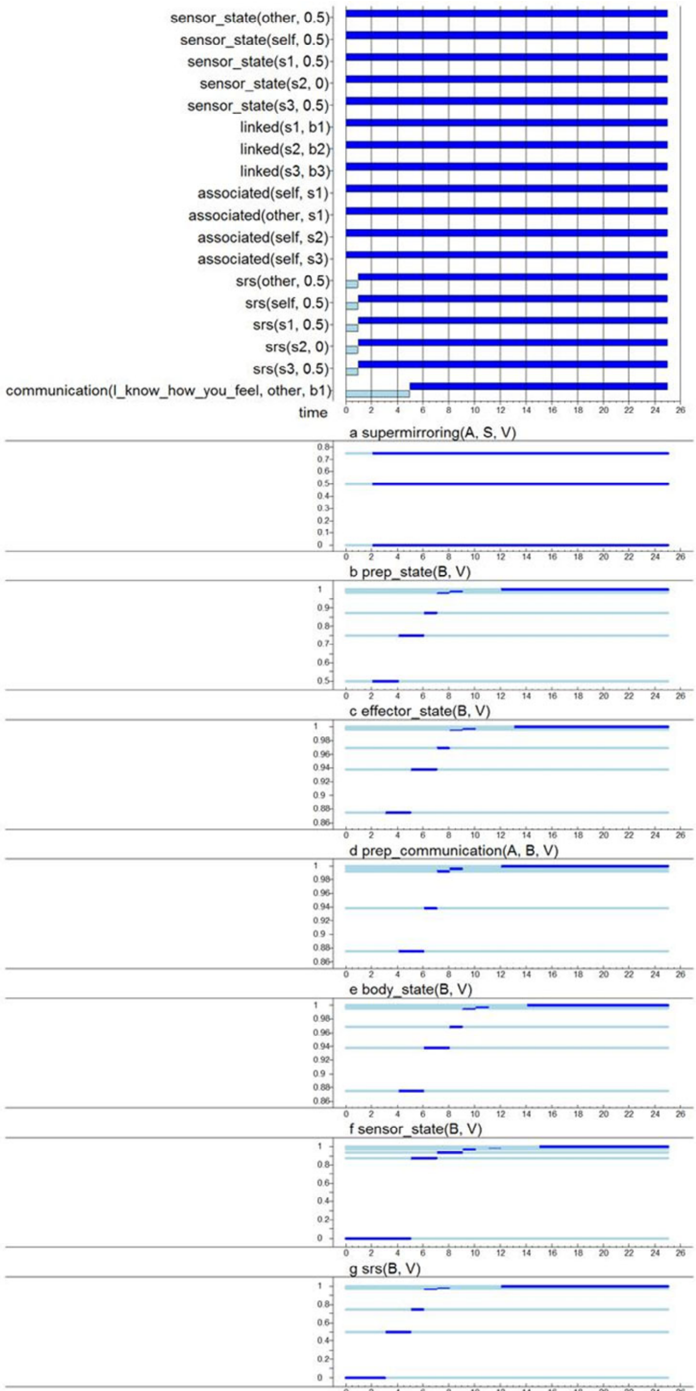

Fig. 2. Example simulation trace for normal functioning

which the indicated state properties hold. Extreme cases are when some of the connection strengths are *0*. Three of such types of malfunctioning are discussed.

Impaired basic mirroring. For example, when both w_3 and w_7 are *0*, from the agent model it can easily be deduced that the preparation state will never have a nonzero level. This indeed is confirmed in simulations (in this case the second graph in the lower part of Fig. 2 is just a flat line at level 0). This illustrates a situation of full lack of basic mirroring of an observed action or body state. Due to this type of malfunctioning no imitation is possible, nor empathic attribution to another agent.

Impaired supermirroring: self-other distinction, control. As another extreme case, when both w_1 and ow_2 are *0*, from the agent model it can be deduced that the super mirroring state for an observed action from another agent will never have a nonzero level (in this case the first graph in the lower part of Fig. 2 is just a flat line at level 0). Therefore, never a communication will be prepared, independent of the level of preparation for a body state. This covers cases in which basic mirroring is fully functional, but self-other distinction as represented in supermirroring is fully absent, and therefore the mirrored action or body state cannot be attributed to the other agent, although they still can be imitated. This is also shown in simulations.

Impaired emotion integration. Yet another extreme case occurs when w_6 and w_7 are *0*, in which case the emotion felt has no integration with the preparation for the action or body state. This covers persons who do not fully affect preparations by emotions felt. Here imitation still may be possible, and even attribution to another agent, but in general will be weaker, also depending on other connections (in this case some of the graphs in the lower part of Fig. 2 have a lower but nonzero level).

Further systematic exploration has been performed in the sense that one connection at a time was changed, from very low (*0.01* and *0.001*), and low (*0.25*), to medium (*0.5*), and high (*0.75*) strengths. The connections w_4, w_5, w_7 and w_{10} showed more substantial deviations from the normal situation in comparison to the connections w_1, w_2, w_3, w_6, w_8 and w_9. As an example, a reduced connection w_5 (e.g., value *0.001*) from preparation to body state makes that it takes longer to reach an increased value for the body state. This corresponds to persons with low expressivity of prepared body states. However, when the other connections are fully functional, still empathy may occur, and even be expressed verbally.

4 Discussion

The presented approach to explore possible relationships between types of malfunctioning of a mirror neuron system and deviations in social behaviour occurring in persons with ASD is based on an executable agent model. Alterations in parameter values of this agent model are used to analyse from a functional perspective which types of malfunctioning of a mirror neuron system can be distinguished, and to which types of deviations in social functioning these types of malfunctioning lead. This approach requires a number of steps. First the normal process must be understood; for this inspiration was taken from the agent model described in [14]. In the case of autism spectrum disorder and the dysfunction of mirror neurons, there was no general description of the process in the sense of formalised causal relations. However, neurological evidence informally described what brain area would have an effect on the performance of certain tasks, resulting in (impaired) behavior. Modeling such causal relations as presented here does not take specific neurons into consideration but more abstract states, involving, for example, groups of neurons. At such an abstract level the proposed agent model summarizes the process in accordance with literature.

The agent model allows to distinguish three major types of malfunctioning, corresponding to impaired mirroring, impaired self-other distinction and control (supermirroring), and impaired emotion integration. Neurological evidence for *impaired mirroring* in persons with ASD is reported, for example, in [9], [16], [21]. This type of analysis fits well to the first case of malfunctioning discussed in Section 4. In [16] the role of super mirror neurons is also discussed, but not in relation to persons with ASD. In [5], [13] it is debated whether the social deviations seen in ASD could be related more to impaired self-other distinction and control (*impaired super mirroring*) than to the basic mirror neuron system; for example:

> 'Recent research has focused on the integrity of the mirror system in autistic patients and has related this to poor social abilities and deficits in imitative performance in ASD [21]. To date this account is still being debated. In contrast to this hypothesis, we would predict that autistic patients likely to have problems in the control of imitative behaviour rather then in imitation per se. Recent evidence has revealed no deficit in goal-directed imitation in autistic children, which speaks against a global failure in the mirror neuron system in ASD [13]. It is, therefore, possible that the mirror system is not deficient in ASD but that this system is not influenced by regions that distinguish between the self and other agents.' [4, p. 62]

The type of impaired mechanism suggested here fits well to the second case of malfunctioning discussed in Section 4.

In [11], [12] it is also debated whether the basic mirror neuron system is the source of the problem. Another explanation of ASD-related phenomena is suggested: *impaired emotion integration*:

> 'Three recent studies have shown, however, that, in high-functioning individuals with autism, the system matching observed actions onto representations of one's own action is intact in the presence of persistent difficulties in higher-level processing of social information (…). This raises doubts about the hypothesis that the motor contagion phenomenon – "mirror" system – plays a crucial role in the development of sociocognitive abilities. One possibility is that this mirror mechanism, while functional, may be dissociated from socio-affective capabilities. (…) A dissociation between these two mechanisms in autistic subjects seems plausible in the light of studies reporting problems in information processing at the level of the STS and the AMG (…) and problems in connectivity between these two regions.' [9, pp. 73-74]

This mechanism may fit to the third case of malfunctioning discussed in Section 4.

The agent-model-based computational analysis approach presented explains how a number of dysfunctioning connections cause certain impaired behaviors that are referred to as typical symptoms in the autism spectrum disorder. The agent model used, despite the fact that it was kept rather simple compared to the real life situation, seems to give a formal confirmation that different hypotheses relating to ASD, such as the ones put forward in [5], [11], [16] can be explained by different types of malfunctioning of the mirror neuron system in a wider sense (including super mirroring and emotion integration). An interesting question is whether the three types of explanation should be considered as in competition or not. Given the broad spectrum of phenomena brought under the label ASD, it might well be the case that these hypotheses are not in competion, but describe persons with different variants of characteristics. The computational analysis approach presented here provides a framework to both unify and differentiate the different variants and their underlying mechanisms and to further explore them. Further research will address computational analysis of different hypotheses about ASD which were left out of consideration in the current paper, for example, the role of enhanced sensory processing sensitivity in ASD; e.g., [6]. Moreover, the possibilities to integrate this model in human-robot interaction may be addressed in further research; see, e.g., [2].

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