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RICERCHE

Inspiring robots: Developmental trajectories of gaze following in humans

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Abstract The ability to respond to gaze cueing is essential for successful social interactions and social learning. An active area of research in human robot interactions (HRI) focuses on the computational encoding of biologically realistic gaze cueing responses in robots. Studies of human development are a primary source of guidance for this field of research. The investigation of how perceived gazes constrain the developmental trajectories of visual attention in humans from childhood to adulthood might reveal important factors to implement realistic gaze following in social robots. This study investigated spontaneous gaze following in 2 and 4-year-old children and adults. Participants saw faces of an adult gazing toward an object. We found that accuracy of gaze following improved significantly with age. The results are discussed considering the development of the executive control of visual attention in humans and its possible implication in implementing gaze following in social robotics.
KEYWORDS: Gaze Following; Eye Tracking; Visual Attention; Social Robotics; Developmental Trajectories

Riassunto *Ispirare la robotica: traiettorie evolutive della capacità di seguire la direzione dello sguardo negli esseri umani* – La capacità di seguire la direzione dello sguardo è essenziale per il successo delle interazioni sociali e per l'apprendimento sociale. Un'area di ricerca particolarmente attiva nell'ambito dell'interazione uomo-robot (HRI – *human robot interactions*) si focalizza sulla codifica computazionale della capacità di seguire la direzione dello sguardo nei robot. Studiare come la capacità di seguire lo sguardo possa influenzare l'attenzione visiva negli esseri umani dall'infanzia all'età adulta può rivelare importanti informazioni per implementare la capacità di seguire lo sguardo nei robot sociali. Questo studio ha indagato la capacità spontanea di seguire la direzione dello sguardo in bambini di 2 e 4 anni e negli adulti. I partecipanti hanno osservato una serie di volti umani con lo sguardo rivolto verso un oggetto. I risultati hanno indicato che l'accuratezza nel *gaze following* migliora in modo significativo con l'età. I risultati sono stati discussi considerando il ruolo del controllo esecutivo dell'attenzione visiva negli esseri umani e le sue possibili implicazioni per implementare l'abilità di seguire la direzione dello sguardo nei robot sociali.
PAROLE CHIAVE: Seguire la direzione dello sguardo; Eye Tracking; Attenzione visiva; Robot sociali; Traiettorie evolutive

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SOCIAL ROBOTICS AIMS TO PROGRAM robots that can interact with humans in the real world thanks to a series of social and communication abilities. The key challenge is that social robots should be able to create their own internal representations.[1] To achieve this aim, robotic scientists have applied developmental psychology to program robots not for the execution of a specific task, but rather for being able to learn new competence autonomously during human-robot interactions.[2] Developmental constraints are embedded into an algorithm to support the learning process. In this way, the design of robotic systems relies on harnessing social learning.[3] Social learning requires shared attention, goals and knowledge. Social eye gaze is a powerful indicator of others' mental states. Robots can use social gaze to establish joint attention when learning from human demonstrations of new skills.[4]

1 Gaze following in social robots and in human-robot interactions.

One approach to implement human-like social gaze in robots is grounded in the science of human cognition.[5] This approach considers human visual attention models as context-dependent systems relevant for programming robots to interact in shared environments.[6] The computational encoding of visual attention models in robots programming allows robots to be reactive to environmental inputs like objects or human actions.[7] According to this model, the relevance of the environmental inputs results from a combination of top-down and bottom-up information processing.[8] The bottom-up processing relies on the saliency of the physical features of the stimuli, like color, motion, intensity, contrast.[9] Top-down processing determines the saliency of the visual inputs based on a personal, social and cultural meaning. Thus, some inputs are relevant because they are more familiar than others or because they relate to goals and intentions.[10] Gaze following is a strategy that humans[11] as well as non-human animals[12] employ to prioritize visual information in shared environments. Top-down mechanisms are crucial in perceiving social stimuli in shared environments, like the direction of other people gazes,[13] while bottom-up information processing is relevant for object perception.[14]

An issue for robotic is when to follow the gaze,[15] by balancing bottom-up and top-down visual attention processing for gaze allocation.[16]

A possible source of guidance for this field of research is the study of human development through quantified observations of people using eye gaze in joint attention scenarios to develop human-like social gaze systems in robots.[17]

2 The development of gaze following in humans

We know a fair bit about how young infants process gaze and use gaze following cues to learn about the world. Gaze following emerges very early on in development. Newborns shift their eyes in the direction of others' eye movements.[18] Between 26 months infants increasingly shift attention between people and objects.[19] A study on 3- month-old infants[20] showed increased processing of objects that had been cued by another person's eye gaze. This ability lays the foundation for joint attention or the ability to share attention to people and objects.[21] At the same time, infants' gaze-following elicits contingent social feedbacks, which encourage them to follow the others' gazes in the future.[22] As a consequence of countless joint attention episodes, individuals learn to prioritize the most salient areas of the visual field highlighted by other people gaze.

Only recently, a new model of joint attention neural network merged the development of gaze following with the emergence of the executive control of visual attention. According to this model, the pathway underlying the voluntary control of oculomotor movements enables gaze following and the intentional gaze alternation between interesting events and social partners.[23] So that joint attention and related social behaviors, like gaze following, are grounded on an executive control of visual attention, which is well developed in adults and still developing in children.[24] Despite this new model of executive joint attention, previous studies on gaze following focused exclusively on infancy or adulthood. New studies are needed to investigate the developmental trajectories of gaze following in joint attention contexts from childhood to adulthood. This information might foster the development of new algorithms to program human-like gaze following in social robots.

The present study investigated how perceived gazes constrain visual attention in humans at different ages using a highly simplified joint attention paradigm. Children at 2 years and 4 years of age and adults freely explored a series of static pictures depicting faces with averted gazes. Two identical objects were positioned close to the faces, at the eye level. One object was in the direction of the eyes (gaze target) and the other one was in the opposite direction (non-gaze target). We know that individuals tend to orient their attention to a target towards which a perceived face is gazing.[25]

We studied gaze following by evaluating participants' looking time at the eyes and the two objects, and participants' accuracy in gaze following. Our stimuli included gender-neutral toys suitable for infants to exclude any possible confounding effect of memory or experience on gaze following. Since the objects were identical and always present contemporarily in the visual field, our paradigm should be particularly suitable to study the effects of emerging (in children) and fully developed (in adults) top-down executive control of visual attention in a highly simplified joint attention context.

We expected an age effect on both accuracy and looking time, with adults being more accurate and showing greater attention to the gaze target compared to children and toddlers. We decided to analyze also the time-course of the looking time to investigate possible differences between groups in the process of visual exploration of the stimuli.

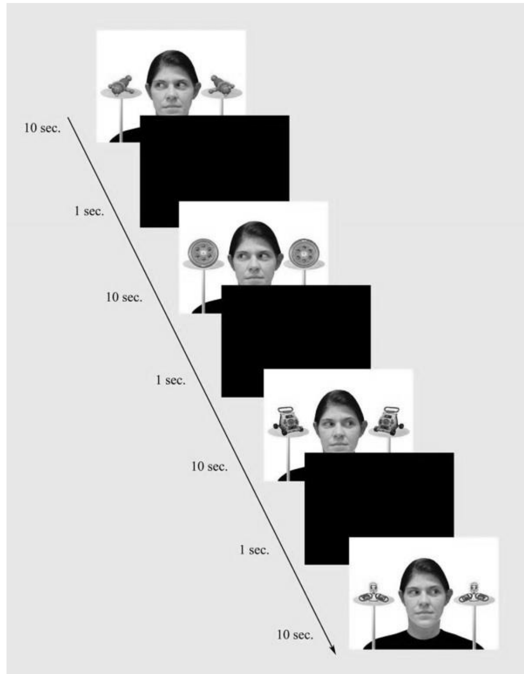


Figure 1. Stimuli adapted with permission from Hoehl and colleagues, showing lateral adult gaze toward the gaze target (GT) and away from an identical object, the non-gaze target (NGT), on the left and right of the screen. There were eight stimuli in total, each presented for ten seconds with a one second inter-stimulus interval. Cf. S. Hoehl, V. Reid, J. Mooney, T. Striano, *What are you looking at? Infant's neural processing of an adult's object-directed eye gaze*, in: «Developmental Science», vol. XI, n. 1, 2008, pp. 10-16

3 Methods

3.1 Participants

We recruited 20 typically developing 2-year-old children (13 males; mean age = 2 yrs and 3 mths ± 0.463) and 20 typically developing 4-year-old children (9 males; mean age = 4 yrs and 9 mths ± 1.687) from the Pediatric Unit of the Azienda Ospedaliera Brotzu in Cagliari, Italy. We recruited 20 typically developing adults (10 males; mean age = 23 yrs ± 1.96) from the Department of Pedagogy, Psychology, and Philosophy at the University of Cagliari. Participants did not have any history of neurological disorder or learning impairments. The study was approved by the IRB committee of the Department of Pedagogy, Psychology, Philosophy of the University of Cagliari (Italy).

4 Materials and Apparatus

4.1 Stimuli

As shown in *Figure 1*, we adapted eight digital photographs (1,000 x 750 pixels) from the study by Hoehl and colleagues (2008a). Photographs consisted of an adult face with a lateral gaze direction toward one of two identical colored toys positioned at eye level on the left and right sides of the image. Four images showed the adult gazing to the toy on the left and four images showed the adult gazing to the toy on the right. We oriented two of the four toy sets toward the face to control for possible effects of orientation.

4.2 Apparatus

We presented the stimuli on a Tobii eye tracker T60 17" TFT flat monitor at a resolution of 1,280 x 960 pixels. The eye tracker recorded eye movements at a frequency of 60 Hz with an accuracy of 0.5 degrees of the visual angle.

4.3 Procedure

Each participant was tested individually in a quiet room. All participants sat approximately 65 centimeters from the screen in a room with lowered blinds and an overhead fluorescent light. Participants completed a calibration with the eye tracker consisting of a red dot moving to five positions on the screen in the corners and center. The experimenter instructed the participants to watch the screen during the testing phase. Each participant saw a fixed sequence of eight pictures. The pictures were presented in two orders counterbalanced in relation to the direction of gaze (left or right), so that, for each age group, 10 participants received the stimuli in the first order and 10 participants received the stimuli in the second order. Each picture remained on the screen for 10 seconds to allow enough time for object orientation. The pictures were followed by a black inter-stimulus screen for 1 second. The total test phase lasted approximately 90 seconds. The eye tracker recorded eye movement for subsequent analysis.

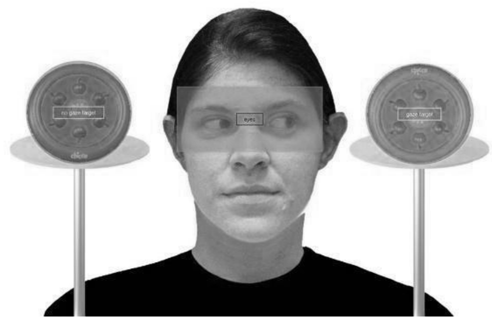


Figure 2. The three areas of interest including the eyes, the gaze target (GT), and the non-gaze target (NGT)

4.4 Coding and Analysis

Eye movement recordings were analyzed off-line using the Tobii Studio 3.2.1 software. A fixation filter (I-VT Filter) with a velocity threshold of 30 degrees/seconds was applied. All fixations shorter than 60 milliseconds were discarded and excluded from the analysis.

First, we evaluated whether gaze biases participant's attention to the gaze target. As shown in *Figure 2*, we defined three Areas of Interest or AOIs: the eyes, the gaze target (GT) and the non-gaze target (N-GT). We controlled for individual differences in the total looking time at the screen by analyzing the proportion of the total looking time to the eyes, the gaze target and the non-gaze target. We calculated the proportion by dividing the total looking time to each area of interest by the total looking time to anywhere on the screen. We applied a 3×3 (group × AOIs) Mixed ANOVA to analyze age related differences.

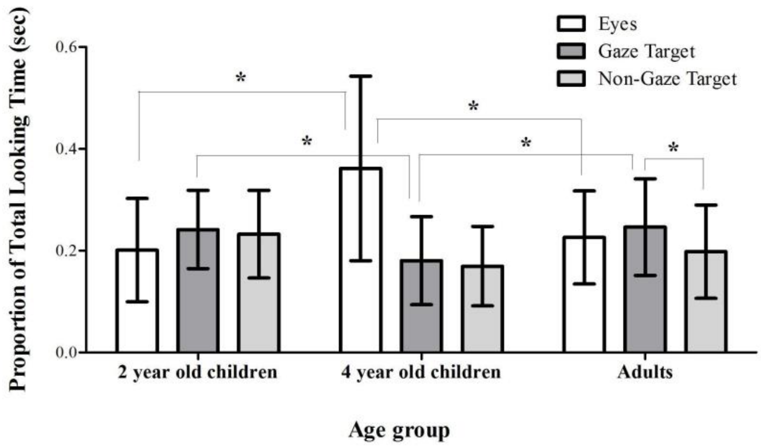


Figure 3. Proportion of total looking time to the eyes, the attended object (Gaze target), and the unattended object (Non-Gaze Target) in 2 year old children, 4 year old children and adults

We also analyzed the time course of the proportion of total looking time to the AOIs by dividing the time of observation into five-time blocks of 2 seconds each. We applied a 3×3×5 Mixed ANOVA comparing proportion of looking time to the areas of interest (eyes, GT, NGT) between groups (toddlers, children and adults) and within five two-second time bins (1-2, 3-4, 5-6, 7-8, 9-10) of the stimuli presentation.

Finally, we evaluated the accuracy of participant's gaze following. We defined the accuracy as a difference gaze score between the number of saccades from the eyes to the non-gaze target subtracted from the number of saccades from the eyes to the gaze target.[26] All recordings were manually coded by a researcher blind to the age of the participants as well as to the research hypotheses. The coding was based on gaze replays (video of the stimulus area with the gaze plots of the infant superimposed) using the Tobii Studio 3.2.1 software (Tobii AB, Danderyd, Sweden). For a saccade to be included in the analysis, participants had to first fixate the adult's eyes and then fixate one of the objects. Trials in which a participant, after the initial fixation at the adult's eyes, looked at the attended object were coded as congruent. Trials in which a participant moved his/her gaze from the adult's eyes to the unattended object were coded as incongruent. The gaze shift needed to move directly from the adult's eyes to the target.

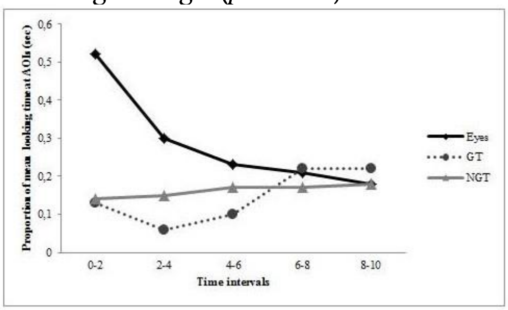
We applied a one-way ANOVA to analyze differences between age groups. A difference gaze score of zero would indicate the same number of saccades from the eyes to the gaze target and from the eyes to the non-gaze target. A positive difference gaze score would indicate more saccades from the eyes to the gaze target than saccades from the eyes to the non-gaze target. We calculated whether the difference gaze score was different from zero with a one-sample t-test. A coder blind to the age groups manually coded frequency of saccades off-line. A second coder evaluated 25% of the recordings with an inter-rater reliability of 0.95.

The assumptions of normality were not violated for the data distribution of the proportion of the looking time and the accuracy. We corrected for multiple testing by dividing the level of significance for the number of comparisons considered in the post-hoc t-tests.

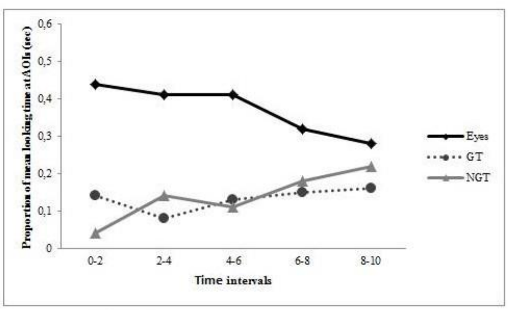
5 Results

5.1 Looking Time Proportions at AOIs

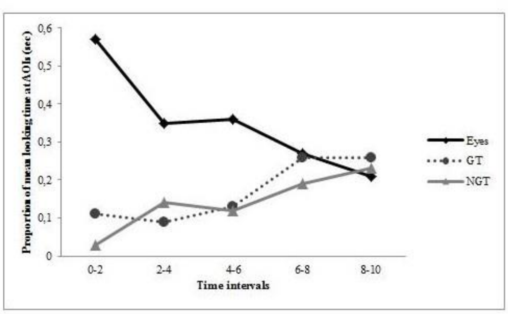
Figure 3 shows looking time proportions at AOIs in the three groups. We applied a 3×3 Mixed ANOVA to analyze age related differences. We found a significant interaction between AOI and age group (F (4, 110) = 7.185, p < 0.001). Post hoc independent sample t-test showed that that 4-year-old children looked longer to the eyes compared to 2-year-old children (p = 0.002) and adults (p = 0.007). Adults looked longer at the gaze target compared to children at both ages, respectively at 2 years old (p = 0.002) and at 4 years old (p = 0.001). Post hoc paired sample t-test showed that Adults looked longer at the gaze target compared to the non-gaze target (p = 0.031).



a) 2 year old children



b) 4 year old children



c) Adults

Figure 4. Time course analysis of the proportion of total looking time at the eyes, the attended object (GT) and the unattended object (NGT), for trial one across five time bins of 2 seconds each for 2 year old children, 4 year old children and adults

5.2 Time course analysis of the looking time proportions at AOIs

A time course analysis of the looking time proportions at AOIs indicated a significant main effect of time (F (4, 196) = 4.093, p < 0.003) and AOIs (F (2, 98) = 30.002, p < 0.001). There was a significant interaction between area of interest and time (F (8, 392) = 17.989, p = 0.032). There was also a significant interaction between time and group (F (8; 196) = 2.159; p = 0.032). *Figure 4* shows the proportion of looking time the Areas of interest for each group for the five-time bins. Post-hoc t test comparisons for paired samples showed that 2-year-old children looked significantly more to the eyes compared to the GT during the time bin 1 (p < 0.001), time bin 2 (p < 0.001), and time bin 3 (p = 0.046). 4-year-old children looked significantly more to the eyes compared to the GT during the time bin 1 (p = 0.004), time bin 2 (p < 0.001), time bin 3 (p < 0.001) and time bin 4 (p = 0.016). Adults looked significantly longer to the eyes compared to the GT during the time bin 1 (p < 0.001), time bin 2 (p = 0.003) and time bin 3 (p < 0.001). There were no significant differences between GT and NGT during the time course in any of the three groups.

5.3 Accuracy of gaze following

Figure 5 shows that accuracy of gaze following improved with age. A one-way ANOVA indicated significant differences between age groups ($F_{(2, 57)} = 3.924$, p = 0.025). 2-year-old children were less accurate than 4 year old children (p = 0.001) and adults (p = 0.014). 4-year-old children were as accurate as adults. A one-sample t-test showed that the performance of 2-year-old children did not differ from chance (p =0.193). The performance of 4-year-old children and adults differed significantly from chance (p = 0.03 and p = 0.04 respectively). This means that 4-year-old children and adults follow gaze accurately.

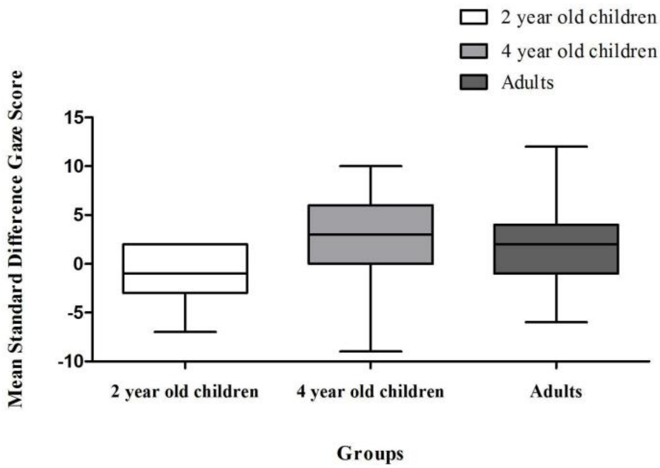


Figure 5. Mean difference gaze score (accuracy) in 2 year old children, 4 year old children and adults

6 Discussion

This study investigated whether gaze following affects looking times to eyes and targets. We found that 2-year-old children distributed their attention equally to the eyes and the two objects. 4-year-old children focused longer to the eyes but observed the two objects for the same extent. Adults looked significantly longer at the gaze target compared to the non-gaze target. These results indicated a stronger effect of gaze on the direction of attention in adults.

The analysis of the time course of the proportion of the looking time at the stimuli indicated that 2-year-old children and adults looked more at the eyes compared to the gaze target during the first six seconds of the stimuli presentation. Children looked more at the eyes compared to the gaze target during the first 8 seconds, which is almost the total duration of the stimuli. These results indicate that 2-year-old children, 4-year-old children and adults constantly prioritize the information provided by the eye-gaze and rely on it. However, only adults looked longer at the gaze target compared to the other groups.

Our results might be interpreted in the framework of the executive network of joint attention.[27] Since the objects presented were identical in their physical properties, only the direction of the gaze should have biased participants' attention to one object more than to the other one. Also, since the objects were contemporary visible all the time, participants had to suppress saccades directed to an object to focus on a competing stimulus to follow the direction of the gaze. Thus, the executive control of attention, fully efficient in adults, should have played a key role on gaze following in this highly simplified task.

The results of our study might inspire robot programming. Previous studies indicated that a robot can learn to perform joint attention abilities in the course of a human-robot interaction in the same way that infants acquire this ability by interacting with a caretaker. Chao and colleagues applied a developmental approach to robotic pointing via human-robot interaction.[28] Developmental constraints have been incorporated into a reinforcement-learning paradigm to establish an understanding of pointing gestures in the perception of both the human and the robot. A similar approach has been applied to implement gaze following in robots to achieve specific conversational functions, like for example turn taking,[29] or during a physical construction task in which assistance was required.[30] Our study indicated that progressive high-level executive control might be a key factor to be included into new algorithms to foster gaze following development in robot-human interaction.

Joint attention abilities play a lifelong role in selecting visual inputs. At the same time, joint attention might be an essential part of relevance detection for robotics.

Whether designing for children or robots, future research is needed to determine the most optimal ways to monitor and drive attention. In the current study we used static visual stimuli. Question remains how the use of dynamic stimuli may have affected our findings. A recent study showed that typically developing children may find dynamic faces more difficult to process.[31] In addition, future research may add vocal cues.[32]

This study has some limitations, that need to be acknowledged. One possible limitation of our study is that we used highly simplified stimuli. The use of these stimuli might underestimate the ability of 2-year-old children to follow the gaze, even though they follow gazes in more natural situations.[33] There are at least three possible explanations for this effect. First, during natural situations adults scaffold infant's attention employing a variety of social cues, like pointing and head movements.[34] In this way, gaze following is facilitated. Second, during natural situations, gaze cues appear very quickly and may last a few seconds in some cases. In our study, the stimuli were still images of a face with the gaze averted for an extended period. Participants therefore had time to look at the gaze target and at the non-gaze target. Future studies are needed to assess these timing effects. Third, during natural situations gaze cues are dynamic and combined with eye contact and other social and non-social behaviors. Research shows that movement makes gaze direction more salient than an averted gaze alone.[35] However, beside these limitations, the internal validity of our study is based on previous studies, showing that across a static and dynamic gaze cue, the pattern of results appeared similar such that the effect of the gaze were equivalent.[36]

Another possible limitation of the study might be the sample size. The sample size of our study is suitable to detect a medium and a large effect size, which indicate that we spotted quite macroscopic differences between the groups. However, a replication of this study with a greater number of participants in each group would allow for a more powerful detection of subtle differences between groups, like for example in the time-course analysis.

Visual attention is a very complex ability, in which several factors are involved. Our stimuli were ideal to evaluate the effect of executive control. Since the two objects were neutral and identical, only the gaze would orient participants' visual attention to the gaze target.

Learning to prioritize relevant social information is a necessary step in social cognition and human machine interaction. This is also an issue when designing robots for populations with visual or related impairments. Further studies are needed to better define, from a developmental perspective, the processing involved in the emergence of an adult-like pattern of visual attention during gaze following. Gaze direction biases human attention to specific inputs of the environment. Top-down executive control of visual attention inhibits the eye-movements toward competing stimuli. This process might be translating into a machine computation. This computation might help robots to select socially relevant information in shared environments. Understanding the mechanisms and development of robotic systems benefits from understanding how human social cognition develops.[37] On the other hand, robots might play a key role in simulating human behavior in highly controlled environment, shedding new light on emerging social abilities from childhood to adulthood.

Notes

[1] Cf. M. Lungarella, G. Metta, R. Pfeifer, G. Sandini, *Developmental robotics: A survey*, in:

«Connect Science», vol. XV, n. 4, 2003, pp. 151-190.

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[5] Cf. K. RUHLAND, C.E. PETERS, S. ANDRIST, J.B. BADLER, N.I. BADLER, M. GLEICHER, B. MUTLU, R. MCDONNEL, *A review of eye gaze in virtual agents, social robotics and HCI: Behaviour generation, user interaction and perception*, in: «Computer Graphics Forum», vol. XXXIV, n. 6, 2015, pp. 299-326.

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[7] Cf. K. RUHLAND, C.E. PETERS, S. ANDRIST, J.B. BADLER, N.I. BADLER, M. GLEICHER, B. MUTLU, R. MCDONNEL, *A review of eye gaze in virtual agents, social robotics and HCI*, cit.

[8] Cf. J.T. SERENCES, S. YANTIS, *Selective visual attention and perceptual coherence*, in: «Trends in Cognitive Sciences», vol. X, n. 1, 2006, pp. 38-45.

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[10] Cf. J. FECTEAU, D.P. MUNOZ, *Salience, relevance, and firing: A priority map for target selection*, in: «Trends in Cognitive Sciences», vol. X, n. 8, 2006, pp. 382-390.

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[14] Cf. E. BIRMINGHAM, W.F. BISCHOF, A. KINGSTONE, *Saliency does not account for fixations to eyes within social scenes*, in: «Vision Research», vol. XLIX, n. 24, 2009, pp. 2992-3000.

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[18] Cf. T. FARRONI, S. MASSACCESI, D. PIVIDORI, M.H. JOHNSON, *Gaze following in newborns*, in: «Infancy», vol. V, n.1, 2004, pp. 39-60.

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[22] Cf. P. MUNDY, *Neurodevelopment of joint atten-*

tion, cit.

[23] Cf. *ibidem*.

[24] Cf. M.R. Rueda, J. Fan, B.D. McCandliss, J.D. Halparin, D.B. Gruber, L.P. Lercari, M.I. Posner, *Development of attentional networks in childhood*, in: «Neuropsychologia», vol. XLII, n. 8, 2004, pp.1029-1040.

[25] Cf. J. Driver, G. Davis, P. Ricciardelli, P. Kidd, E. Maxwell, S. Baron-Cohen, *Gaze perception triggers reflexive visuospatial orienting*, in: «Visual Cognition», vol. V, n. 5, 1999, pp. 509-540.

[26] Cf. T. Falk-Ytter, E. Thorup, S. Bölte, *Brief report: Lack of processing bias for the objects other people attend in the 3-year-olds with autism*, in: «Journal of Autism & Developmental Disorders», vol. XLV, n. 6, 2015, pp. 1897-1904.

[27] Cf. P. Mundy, *Neurodevelopment of joint attention*, cit.

[28] Cf. F. Chao, Z. Wang, C. Shang, Q. Meng, M. Jiang, C. Zhou, Q. Shen, *A developmental approach to robotic pointing via human-robot interaction*, in: «Information Sciences», vol. CCLXXXIII, n. 1, 2014, pp. 288-303.

[29] Cf. S. Andrist, B. Mutlu, M. Gleicher, *Conversational gaze aversion for virtual agents*, in: E.R. Aylett, B. Krenn, C. Pelachaud, H. Shimodaira (eds.), *Intelligent virtual agents*, Springer, Cham 2013, pp. 249-262.

[30] Cf. K. Sakita, K. Ogawara, S. Murakami, K. Kawamura, K. Ikeuchi. *Flexible cooperation between human and robot by interpreting human intention from gaze information*, in: «IEEE/RSJ International Conference on Intelligent Robots and Systems», vol. I, 2004.

[31] Cf. B.M. Stoesz, L.S. Jakobson, *Developmental changes in attention to faces and bodies in static and dynamic scenes*, in: «Frontiers in Psychology», vol. V, 2014, Art.Nr. 193.

[32] Cf. E. Parise, A. Cleveland, A. Costabile, T. Striano, *Influence of vocal cues on learning about objects in joint attention contexts*, in: «Infant Behavior & Development», vol. XXX, n. 2, 2007, pp. 380-384.

[33] Cf. G. Butterworth, N. Jarrett, *What minds have common in space: spatial mechanisms serving joint visual attention in infancy*, cit.

[34] Cf. T. Striano, D. Stahl, *Sensitivity to triadic attention in early infancy*, cit.

[35] Cf. *ibidem*.

[36] Cf. J.K. Hietanen, J.M. Leppänen, M.J. Peltola, K. Linnaaho, H.J. Ruuhiala, *Seeing direct and averted gaze activates the approach-avoidance motivational brain systems*, in: «Neuropsychologia», vol. XLVI, n. 9, 2008, pp. 2423-2430; E.F. Risko, K.E. Laidlaw, M. Freeth, T. Foulsham, A. Kingstone, *Social attention with real versus reel stimuli: Toward an empirical approach to concerns about ecological validity*, in: «Frontiers in Human Neuroscience», vol. VI, 2012, Art. Nr. 143.

[37] Cf. S. Grossberg, A. Meltzoff, J. Movellan, N. Newcombe (eds.), *Social cognition: From babies to robots*, in: «Neural Networks», vol. XXIII, n. 8-9, 2010, Special Issue, pp. 939-1134.

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