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Reachable by walking: inappropriate integration of near and far space may lead to distance errors

Beata J. Grzyb[1], *Vicente Castelló*[1] *and Angel P. del Pobil*[1,2]

[1]Robotic Intelligence Lab, Jaume I University, 12071 Castellon, Spain
[2]Interaction Science Dept., Sungkyunkwan University, Seoul, Korea
{grzyb,castellv,pobil}@icc.uji.es

Abstract

Our experimental results show that infants while learning to walk intend to reach for unreachable objects. These distance errors may result from inappropriate integration of reaching and locomotor actions, attention control and near/far visual space. Infants during their first months are fairly immobile, their attention and actions are constrained to near (reachable) space. Walking, in contrast, lures attention to distal displays and provides the information to disambiguate far space. In this paper, we make use of a reward-mediated learning to mimic the development of absolute distance perception. The results obtained with the NAO robot support further our hypothesis that the representation of near space changes after the onset of walking, which may cause the occurrence of distance errors.

Index Terms: motor development, space awareness, distance perception

1. Introduction

Infants discover and learn about their environment and about their own body through their actions. Space perception, and distance perception in particular, is action-specific [1]. Different types of actions are possible depending on the distance away of a given object. For example, if the object of interest is close to the body (in near/peripersonal space), reaching and then grasping action may be performed. If the object is beyond reach (in far/extrapersonal space), then locomotor action is needed to reach and finally grasp the object. To accomplish such a task successfully, the brain must compute the distance of the object from the agent's body correctly and activate the maps for near and far space representations appropriate to the computed distance [2]. The coding of spatial positions may not only be related to the computation of the absolute distance between the body and the stimulus, but also related to the execution of specific actions in space, such as reaching or locomotion.

Considering the problem from a develepmental perspective, not all actions are available to the infants from the beginning. Although prelocomotor infants may have depth information available, such as stereopsis, yet they lack knowledge of the absolute distance of an object in space beyond reach. Self-produced locomotion helps to calibrate visual information, resulting in more precise distance estimation of the object [3]. Such an action-based distinction between near and far space seems to be at the heart of Piaget's theory of spatial cognition in the sensorimotor period. According to his theory near space is the space calibrated by reach, and far space is that calibrated by self-produced locomotion.

Our empirical studies showed that 12-month-old infants reach significantly more than 9-month-old for unreachable objects, and that this momentary disruption in perceived reachability may be related to infants' walking ability [4]. There are a number of ways in which walking may affect decisions to reach. Our previous work focused on motivation as a possible explanation of older infants' behavior [5]. More specifically, we suggested that infants in a new upright posture fail to correctly update the boundaries of their reachable space because of their decreased ability to learn from the errors. Such blocked ability to learn from negative outcome was suggested to be tightly connected to the sense of control and to result from extremely high level of self-efficacy. Since a primary motive for walking is to reach for something, such a diminished ability to learn from the errors may help infants to fine-tune their newly acquired walking skill. An alternative explanation of distance errors was also investigated, that is that the processes responsible for integration of different visual depth cues may reorganize themselves at the onset of walking so as to incorporate depth information from self-motion-based depth cues [6]. The developmental process of distance perception for action was mimic by using a reward-mediated learning and the results showed an increase in near/far space confusions after the onset of walking.

This paper investigates in more detail the recalibration process of distance information in accordance with new motoric factors and its relation to the occurrence of distance errors in infants. We suggest that for a novice walker getting an object one wants may consist primarily of orienting the body in that directions with the hands out, and moving until you arrive. Attending to the precise distance, in the moment may just not be as important as it is for younger nonwalking infants. Herein, the walking experience is indispensible for learning the representation of far space, and for the proper integration of reaching and locomotor actions, attention control and near/far visual space. The results obtained with the NAO robot support further our hypothesis that the representation of near space changes after the onset of walking, which may contribute to the occurrence of distance errors.

2. Distance errors in infants

The main objective of our experiments was to see how infants recalibrate or scale perceptual information for action, and more specifically, how their assessment of the reachability of objects placed at different distances changes as their bodies and motor skills change. Young infants show an early distinction between what is and what is not reachable that is evident in their reaching behavior itself. At or rapidly after the onset of reaching (around 4 months), infants clearly distinguish reachable and nonreachable distances as they systematically do not to reach to far objects. The purpose of our experiments was to examine

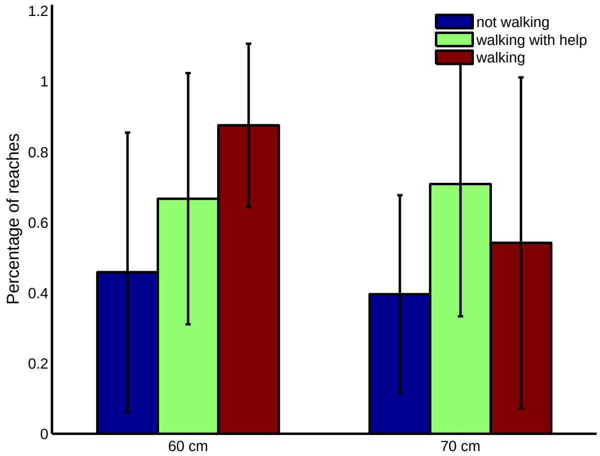


Figure 1: *Mean percentage of reaches to objects placed at far distances for 12-month olds: non-walkers, walkers with help, and independent walkers.*

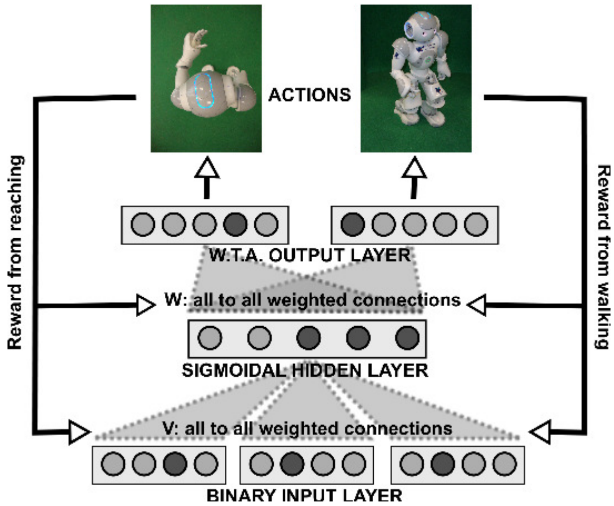


Figure 2: *General scheme of the reward-based learning model.*

the boundary between distances at which older infants, 9- and 12-month olds, do and do not reach to objects.

In total, 8 9-month-old and 8 12-month-old infants participated in our first study. Participants were seated in a modified baby car seat. The chair allowed infants to lean freely forward without a danger of falling. The balls on dowels were presented through a colorful display – like a puppet theater – that also separated the experimenter from the infants. The balls were presented at distances 30, 37, 47, 60, and 70 cm from the infant. There was no explicit reward provided to the infants after the trial for any tested distance. This helped us to avoid situations where the infants could learn to make reaching movements just to communicate their interest in obtaining a reward.

The pattern of 9-month-old reaches indicated that infants decisions to reach – in some way – take into account the relation between the body size and skill and distance of the target. For the 9-month olds, attempt reaching and successful reaching were aligned. The 12-month olds, in contrast, consistently and persistently reached to objects at distances patently unreachable showing no adjustment of their behavior with experience in the task. For the infants in the experiment, it is likely that few of the 9-month olds were walking or "cruising" upright while holding on to a support but it is highly likely that many of the 12-month olds were walking or spending time in some form of pre-walking activity in an upright posture. Thus, this developmental decline in the alignment between attempted and successful reaching distances could be related to the transition to walking.

We extended our experiment recruiting more infants with different walking abilities. A final sample constituted of 24 infants categorized into 3 equal-number groups, that is non-walkers, walkers with help, and independent walkers. Fig. 1 shows mean percentage of reaches to objects placed at far distances. As is clearly seen, walkers (with and without help) reached more for distant distances than non-walkers.

3. Reinforcement learning model

Since a reward-mediated learning have been shown to successfully mimic the development of near-optimal integration of visual and auditory cue in infants [7], a similar approach is taken here. The outline for proposed model is presented in Fig. 2. The model is composed of two – not interconnected at the moment – neural networks for reaching and for walking actions. The network architectures and neurons connections are the same in both networks, and thus will be discussed together.

A three-layer neural network is used to approximate the state-action mapping function. The input layer of the network is composed of n (in our case $n = 62$) binary neurons, that cover the range of distances from $13cm$ up to $142cm$. It is worth mentioning that the input layer may easily be extended to include more depth cues, such as stereopsis or motion parallax (as it was done in [6]). For the sake of simplicity, however, in this work we use just familiar size depth estimation. The activity of the neurons x_i is one at depth estimated by the corresponding cue, otherwise zero.

The input neurons are all-to-all connected with weights $v_{i,j}$ to j neurons in the hidden layer. A sigmoidal transfer function on the sum of the weighted inputs gives the outputs y_j of the hidden neurons:

$$y_j = \frac{1}{1 + e^{-\sum_i v_{i,j} x_i}} \tag{1}$$

The hidden neurons are fully connected to output neurons k with weights $w_{j,k}$. All weights are drawn from uniform distributions, $v_{i,j}$ between -0.1 and 0.1, and $w_{j,k}$ between -1 and 1.

Each output units represents an action. The representations of the action and their metric units are different in the both networks. While the distances in the network for reaching are represented in centimeters, the distances in the network for walking are represented in steps. In case of the network for reaching, k_r ($r = 62$) reaching actions are possible and the binning size, that is the parameter responsible for discretization of the action space is set to $1\ cm$. It is worth mentioning that the actual boundary for reachable space for the NAO robot is approximately $21cm$, and fewer neurons, in fact, are needed to encode its reachable space. Nevertheless, we set a larger number of output neurons to observe how the border of the reachable space can emerge dynamically during the learning process. In the case of the network for walking, k_w ($w = 4$) actions are possible, and the binning size is set to $1\ step$.

The activation of the output neurons z_k is given by the weighted sum of the hidden layer activity, representing an approximation of the appropriate Q-value. Based on the network's outputs, one action is chosen according to the *softmax* action selection rule [8]:

$$P_t(k) = \frac{e^{Q_t(k)/\tau}}{\sum_{b=1}^{n} e^{Q_t(b)/\tau}} \quad (2)$$

where $P_t(k)$ is the probability of selecting an action k, $Q_t(k)$ is a value function for an action k, and τ is a positive parameter called *temperature* that controls the stochasticity of a decision. A high value of τ allows for more explorative behavior, whereas a low value of τ favors more exploitative behavior. We start with a high temperature parameter $\tau = \tau_0$ ($\tau_0 = 10$), so that the selection of action is only weakly influenced by the initial reward expectations. In our experiments, τ decreases exponentially with time $\tau(t) = \tau_0^{(\frac{v_\tau - t}{v_\tau})}$, where $\tau_0 = 10$ and $v_\tau = 50000$ in case of the network for reaching and $v_\tau = 5000$ in other case.

After performing the selected action $\hat{k}$ the true reward $r(\hat{k})$ is provided. The reward is maximal when $\hat{k}$ equals the true object position k_t, decaying quadratically with increasing distance within a surrounding area with radius ρ and zero otherwise ($\rho = 4$ in case of the network for reaching, and $\rho = 0$ in other case).

$$r(\hat{k}|X) = max(0, (\rho - |\hat{k} - k_t|))^2 \quad (3)$$

To minimize the error between the actual and expected reward, we make use of gradient descent method which is widely used for function approximation, and is particularly well suited for reinforcement learning.

$$v_{i,j}(t+1) = v_{i,j}(t) - \epsilon(r_{\hat{k}} - z_{\hat{k}})(-w_{j,\hat{k}})y_j(1-y_j)x_i \quad (4)$$

$$w_{j,\hat{k}}(t+1) = w_{j,\hat{k}}(t) - \epsilon(r_{\hat{k}} - z_{\hat{k}})(-y_j) \quad (5)$$

Herein, only the output weights $w_{j,k}$ connected to the winning output unit $\hat{k}$ are updated. The learning rate ϵ, decreases exponentially, according to the formula $\epsilon(t) = \frac{\epsilon_0}{ceil(\frac{t}{v_\epsilon})}$, where $\epsilon_0 = 0.05$ (for both networks), and $v_\epsilon = 50000$ in case of the network for reaching, and $v_\epsilon = 200$ in other case.

4. Experiment with the robot and results

One of the shortcomings of the reward-based methods is the large number of training examples needed for the neural network to converge. In the case of network for reaching we need approximately $t = 50000$ time steps. Such a large number of repetitions would be extremely time-consuming and unfeasible for any robotic platform. Therefore, initial weights of the neural networks are trained offline with the real data collected with the use of our robot, and then tested online on our robotic setup.

4.1. Robotic platform

Aldebaran's comercially available humanoid robot NAO with 25 DoF is used as a platform for the examined depth estimation methods. The robot is provided with two identical video cameras placed in the forehead. Their locations, however, does not allow the use of stereo vision methods for depth calculation. Within our framework, we provided the NAO robot with the reaching module, that is based on a radial basis functions (for details refer to [9]). For walking behavior, we make use of the robot built-in functions.

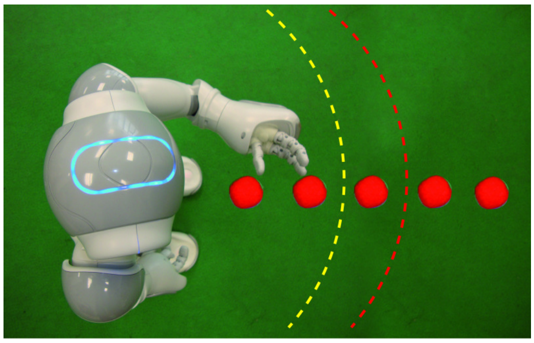


Figure 3: *Experimental setup in our study with the robot.*

4.2. Experimental setup

Our experimental setup is shown in Fig. 3. Similarly to the infant experiments, the main objective of the robot was to decide whether to reach or not for the ball. Since the NAO robot is much smaller than an average 12-month-old infant, we had to adjust the testing distances to reflect its size. Five different distances were tested, 2 close distances that easily allow the robot for reaching and grasping the objects (13 cm and 15 cm), one distance precisely at the border of reachable space (21 cm), and two distances clearly outside of the reachable space (23 cm and 26 cm). To account for the factors (others than distance) that influence the decision to reach, such as motivation or attention, we introduced some random variation on 20% of the robot's decisions.

4.3. Experiment 1: Before the onset of walking

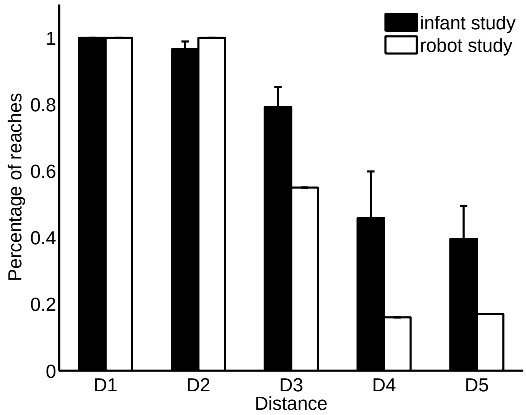
To simulate a developmental path of absolute distance perception in infants, first we train the network for reaching action, which basically constitute the near space representation. The training begins with a high temperature parameter τ, so that the selection of action is only weakly influenced by the initial reward expectations. The network is trained during 50000 time steps.

The activation of the output neurons represents a reward predictions (Q-values) which may be used to distinguish between reachable and non-reachable space. A high value of reward prediction corresponds to the near and easily reachable distance, whereas a low Q-value represent far – unreachable – distance.

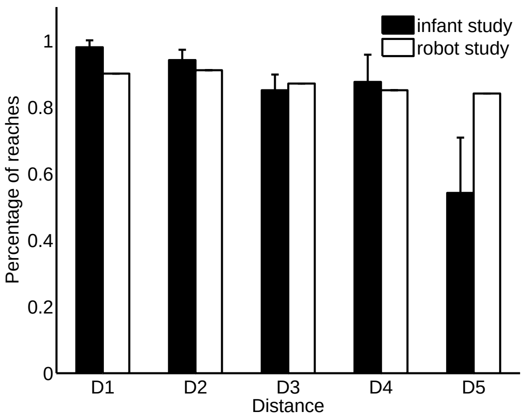
The weights of the neural network are trained offline and then are employed in our robotic setup. The robot is presented with a ball at one of the five distances. Each test trial is repeated 10 times. The mean reaching attempts of the robot are shown in Fig. 4(a) along with the mean reaching attempts of 12-month-old non-walking infants. As it can be seen, the results obtained with the robot closely match the empirical results with human infants.

4.4. Experiment 2: After the onset of walking

The training of the network for walking begins with a high value of τ, so that the selection of action is only weakly influenced by the initial reward expectations. The weights of the network for reaching are also trained so that the robot can estimate the distance of an object before it gets close enough to reach for it. Simply speaking, the networks estimate the necessary number of steps for walking and the remaining distance for reaching.



(a) *Before the onset of walking*



(b) *After the onset of walking*

Figure 4: *Mean reaching attempts to various distances in the empirical experiment with infants and the robot experiment.*

The weights learned on simulation are once again employed in our robotic setup. Here, the execution of walking is blocked, similarly as in our empirical study where the infant was sitting in a chair with a seatbelt fastened. This trial test is repeated 10 times for each distance. The mean reaching attempts of the robot are shown in Fig. 4(b). It can be seen, that the representation of the near space has changed, and the distances that previously were unreachable now became reachable. It is worth mentioning, that when the execution of walking was enabled, the robot in all cases was able to walk towards and then reach and finally grasp the object successfully with the distance information provided by the networks (the error of the reaching distance was less than $1\ cm$).

5. Discussion

The representation of space, not only far space, but also near space changes with the onset of locomotion so that the newly emerging representation of far space can be integrated into a coherent space representation. Planning and coordination of walking and reaching behaviors are only possible when a certain level of the infant's walking proficiency has been achieved, as well as the infant has sufficient cognitive capacity to process and store the action plan. Novice walkers may reach more frequently for objects at far distances because they are not able to mentally immobilize the body's remaining degrees of freedom. The proper coordination of near and far space, and the locomotion and reaching action is required for successful executing of actions in far space. Our robot experiment suggest that had not been fastened by the seatbelt, the infants in our study would actually walk (possible with an extended hand) to reach and finally grasp the object at far distances. Further empirical experiment would be needed to verify this hypothesis.

The proposed mechanism is just one of the possible explanations of the observed distance errors in early development. Our previous works investigated the role of locomotion in observed changes in infants motivation as well as changes in the integration of various previously unattended depth-specifying cues. This paper investigated in more detail the possible mechanism for calibration of absolute distance perception that also alters the representation of near space. Neththertheless, these explanations are not mutually exclusive, and may be overlapping in underlying mechanisms.

6. Conclusions

This paper presented the phenomenon of distance errors seen in infants during the transition to walking and suggested that the calibration of absolute distance perception contributes to the appearance of these errors. The results obtained with the use of the reward-mediated approach to learning taken here provided further support for our hypothesis.

7. Acknowledgements

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