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Timing sensory integration for robot simulation of autistic behavior

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Abstract— **This paper applies the dynamic neural field model [1,2,3] to multimodal interaction of sensory cues obtained from a mobile robot, and shows the impact of different temporal aspects of the integration to precision of movements. We speculate that temporally uncoordinated sensory integration might be a reason for the poor motor skills of patients with autism. Accordingly we make a simulation of 2D orientation behavior, and suggest that the results can be generalized for reaching to grasp movement that is performed in three dimensional space. Our experiments show that the impact of temporal aspects of sensory integration on the precision of movement is concordant with behavioral studies of sensory integrative dysfunction and autism. Specifically, the simulation predicts that distant grasping will be performed properly by autistic people in general, except if it requires a combination of proximal and distant sensory information, as in the case of proximal obstacles. Our simulation and the robot experiment will be implemented in a humanoid robot and will serve as a basis for games for behavioral training of autistic children.**

I. INTRODUCTION

AUTISM is the most common condition in a group of developmental disorders known as the autism spectrum disorders (ASDs) [42]. It is characterized by impaired social interaction, problems with verbal and nonverbal communication, and unusual, repetitive, behaviors and interests. Movement disturbance symptoms in individuals with autism have long not been considered an important symptom. During the last decade, Leary and Hill [4] have offered a radical perspective on this subject. After thorough analysis of the bibliography on movement impairments in autism they outlined how deficits in movement preparation and execution could lead to many of the behaviors exhibited by individuals with autism. Difficulties in planning and executing simple discrete movements, can lead to problems in learning to coordinate diverse muscle groups into a unitary movement pattern. Moreover, when a person is unable to respond to another's action in a timely fashion they will miss the positive reinforcement associated with interpersonal interaction.

Behavioral evidence of human perception and action indicates that organisms make use of multisensory stimulation. Under normal circumstances, multisensory stimulation leads to enhanced perceptions of, and facilitated responses to, objects in the environment (e.g. [5][6][7]). But literature shows that imprecise grasping or other motor or executive dysfunctions observed in autistic patients are caused by a disturbance in a dynamic mechanism that involves multisensory processing and integration. This can be caused by discrepancies between stimuli that are normally concordant. In these circumstances, multisensory stimulation actually leads to inaccurate perceptions and responses, regarding location, identity, and timing. Temporal binding for instance is identified as a dynamic mechanism that is disrupted and likely implicated in the perceptual as well as higher order deficits observed in autism (Brock et al. [8]). In other studies, atypical processing is specifically associated with enhanced sensory processing or discrimination in various modalities [9][10][11]. Some studies argue for a broader neurological problem such as an executive function deficit in the coordination of sources of information from different modalities [12][13][14].

All these works suggest that the dynamic aspects of integration of multisensory input influences the forming of coherent perception, planning, and coordination of action.

Even more concrete, many studies assume that simple motor planning is intact but that the use of externally guided visual feedback is diminished, affecting the quality of motor performance, postural stability, and the lack of effective sequencing of actions [15][16][17][18]. Thus, perceptually challenging tasks that require smooth integration of visual with vestibular-proprioceptive information, for example, may be particularly difficult to perform and could result in poor quality of motor performance on complex tasks.

We test this assumption by simulating the dynamic mechanism of temporal multisensory integration in order to investigate how the atypical forming of coherent perception might influence coordination of action, and compare the results with experimental studies by typical and autistic patients.

Temporal multisensory integration has previously been discussed in the context of autism in [8] [19] in attempts to obtain a clear understanding of the underlying biological mechanism of interaction and to simulate it in [20][21] in the robotics setting in [22][23], and implicitly in many other robotics studies. Masterton and Biederman [15] in particular have shown that a proper interplay between integration of distal (visual) and proximal (proprioceptive) cues is essential by grasping. We simulate the integration of these cues on a mobile robot in a two-dimensional plane. A very important point is that the integration process that causes the movement behavior is approximated by a dynamic mechanism.

Proper modeling of dynamic (or temporal) integration mechanisms requires a dynamic neural model. The mainstream connectionist methods such as self-organizing or supervised feed-forward networks, and Hopfield type recurrent networks, produce static outputs because their internal dynamics lack feedback loops, and their input space is static. Therefore they are suitable for modeling static behaviors. We are interested in a neural system that can spontaneously exhibit several dynamic behaviors derived from the interaction between changing input and complex inner dynamics. However, for the sake of controllability and computational expense, we have chosen the model that requires the least complexity. Schöner and colleagues [2[2][23][24] have adapted the dynamic neural field model of Amari [1] for controlling mobile robots and robot-manipulators. It produces smooth behavioral trajectories satisfying more than one external variable. In this model the attractor is a fixed point, but a continuous attractor is approximated in sequential steps. The system shifts from one attractor to the other through input-dependent variations. More-complex dynamic models that have continuous attractors may be very demanding computationally.

This paper is organized as follows. Section 2 discusses the method used for sensory integration, the experiment design, and the results of a computer simulation. Section 3 shows the results of robot simulation. The results are discussed in Section 4.

II. TEMPORAL MULTISENSORY INTEGRATION

A. *The dynamic neural field model for multisensory integration*

The dynamic neural field (DNF) model has been proposed as a simplified mathematical model for neural processing [1],[2],[3]. The main characteristics of this model are its inherent properties for stimulus enhancement and cooperative and competitive interactions within and across stimulus-response representations.

Recently Erlhagen and Schöner [24] formalized the extension of the theoretical model to the dynamic field theory of motor programming, explaining how it could be used for robotics and behavioral modeling applications. The DNF model has been used in robotics for navigation and manipulation of objects [25][26][27], for multimodal integration [28], and for imitation [29]. Applications feature biologically convincing methods that can optimize more than one behavioral goal, contradictory sensory information, or sensory-motor task that requires common representation. Iossifidis and Steinhage [26] applied the dynamic neural field model to control the position of the end-effectors of a redundant robot arm. Two problems were solved by this implementation: a smooth end-effectors trajectory is generated, and obstacles are avoided. Faubel and Schöner [25] use the dynamic neural field model to represent the low-level features of the object such as color, shape, and size. The fast object recognition achieved is beneficial for an interaction with a human user. Thelen et al. [29] have modeled the dynamics of the movement planning by integrating the visual input and motor memory to generate the decision for the direction of reaching.

The mathematical description of the dynamic neural field model incorporates the formation of patterns of excitation, their interaction, and their response to input stimuli. The basic equation of a one-dimensional homogeneous field of lateral inhibition can be represented in the following way:

$$\tau\frac{\partial}{\partial t}u(x,t) = -u + \int_0^{180} w(x-y)f[u(y)]dy + h + s(x,t) \qquad (1)$$

where

- τ is the time constant for the dynamics of a neuron
- x and y are the located positions of neurons
- u is the average membrane potential of neurons located at position x at time t
- *w* is an interaction kernel between neuron at position *x* and its neighbors, e.g. at any position *y*
- *f* is the firing rate of the neuron at position *y*; here the unit step function (Heaviside step function) is used
- h is the resting potential
- s(x,t) is the input stimulation level at position x at time t.

A feature of the model that is interesting for us is that it possesses dynamic properties useful for multisensory and sensory-motor integration. We suggest that the dynamic characteristics of the model can be exploited for investigating the temporal aspects of multimodal integration. The temporal window for integration is shown to have an impact on the multisensory interaction, so we investigate the possibilities for its adaptation within the neural field model and its impact on the computational outcomes. The presentation of the sensory cues within the DNF model is in the form of Gaussian distributions. We tune the variance of these distributions according to the experimental findings, and experiment with the delay in the presentation of each cue in accordance with the realistic times of sensory processing of different modalities, while, of course, following the restrictions of the experimental platform.

B. *Experimental setting*

We intend to test the temporal aspects of multimodal interaction in grasping. At the period the experimental work was performed, we had only available a mobile robot lacking human arm appearance. Therefore, the action of the robot was defined as turning towards, and approaching a target object that is intended to be grasped. Our experiments are therefore restricted to a two-dimensional task of reaching a target.

Mainly due to its simplicity and to keep the computational cost low, one dimensional DNF model was used. The output potential of the DNF model defines the turning angle of the robot in a two dimensional plane. The neural field consists of 36 neurons representing the range from 0 to 180 degrees; with a step size of 5 degrees. The positive X-axis was chosen as the zero degree direction, and the angle was measured counterclockwise. To solve numerically Equation 1 we used Euler method, since dt_{Euler} is small in comparison with τ:

$$\tau\frac{\partial}{\partial t}u(x,t) \approx -u + \sum_{i=0}^{N-1} w(x_j - y_i)f[u(y_i)] + h + s(x_j,t) \qquad (2)$$

where:

$$y_i, x_j \in [0, \ldots N] \qquad (3)$$

$$x = \frac{x_j}{N}180 \qquad (4)$$

$$y = \frac{y_i}{N}180 \qquad (5)$$

and N = 36. For the DNF model the sensor data must be represented in the form of the heading angle of the robot.

Based on earlier findings [22][30] two complementary sensory cues are necessary and sufficient for reaching, as well as for precision gripping by the robot. An example of two complementary sensory cues is proprioception and vision. In this application, we assume that the robot always sees the target at a fixed direction that is located at some distance in front of the robot. Then, the robot has to move from the initial position by turning to the target direction and move to the target. The proprioceptive or self-motion information is the angular deviation of the head direction of the robot from the initial position. Vision data is used for spotting the landmark or goal direction. It must be noted here, that the number of the sensors is not directly related to the dimension of the DNF. An important point is that the data from each sensory cue must be represented in the domain of planning field of the DNF. The other parameters of DNF were tuned empirically, taking the suggestions from [27] into account.

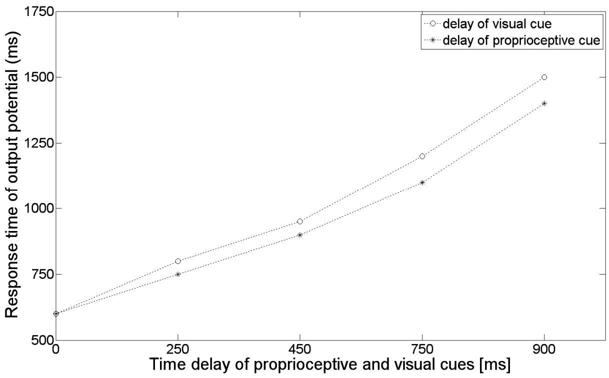
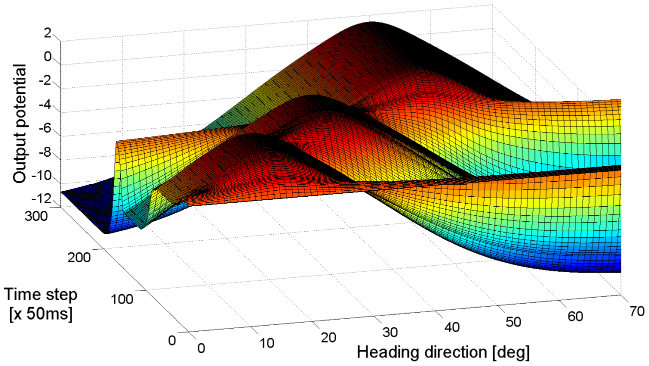


Fig. 1. The time to generate the output potential when each cue is delayed.

The heading direction is defined by the output potential that is generated after the integration of both cues. The robot will typically find a compromise between target direction and obstacle-free space. The DNF model would supply a smooth solution to this problem, once the model parameters are tuned for the particular application. A computer simulation is used for tuning the parameters.

One of the reasons for choosing the DNF model for sensory interaction is that it uses a window of time to combine all the sensory stimuli and to make a decision accordingly. Experimental studies of sensory integration postulate that there is a window of time during which the stimuli must be integrated if they are to produce the perception of a unitary sensory event [31][32][33][34][35][36].

The window for temporal integration is defined by the processing time required for the visual and the proprioceptive cues as suggested by the experimental studies. Based on suggestions from literature, the time window should be around 300 – 400 ms. However, due to the hardware constraint, the time window for the robot was set as 500 ms.



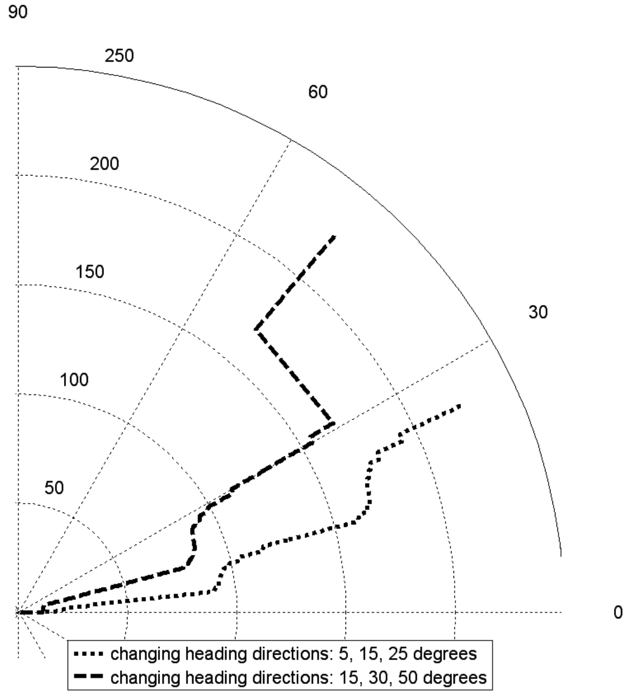


Fig. 2. Upper: the output potential with heading direction changing with 15 - 30 - 50 degrees; Lower: the trajectories of the robot in polar coordinates with heading direction changing correspondingly with 5 - 15 - 25 , and 15 - 30 - 50 degrees.

Our hypothesis is that a delay in the activation corresponding to each of the sensory cues may cause or contribute to imprecise motor behavior. With the following experiment we are going to test the impact of the delay in the activation caused by each of the sensory modalities. We experimented with different delay intervals.

To verify our hypothesis with DNF, we used a two step process. First, the experiment was simulated on Webots (http://www.cyberbotics.com/), and second, the experiment with an e-puck robot [41] was conducted. The data from the Webots simulation were analyzed with MATLAB. The experimental arena is set up as an X-Y plane for the computer simulation. As discussed in [22] (see also [30]), the combination of visual and proprioceprive cues gives complementary sensory information for tasks as grasping and navigation. The complementarities of the cues refers to whether the sensor gives information about the movement of the robot (simulated or physical) or about the external landmark or target information. The combination of these cues has been identified important by goal-directed motor actions by humans. Masterton and Biederman [15] discuss the importance of the combination of these cues for goal-directed motor actions by patients with autism.

To test the effect of cue delay on the sensory integration, each cue signal was delayed by a different time interval when a goal finding task was performed. Figure 1 show the response times for the robot to decide the direction of movement. The visual cue delay has a more significant effect on response time than the proprioceptive cue.

To get further information on the delay effect for each cue, the experiment of changing heading direction was carried out for three successive steps.

Several tests were made with a simulated robot that performs target-following tasks. In each test, after the robot determined a heading direction, the target was moved so that the heading direction of the robot changed by different angles. Figure 2 depicts trajectories with changes of the heading direction corresponding to 5 - 15 - 25 degrees and 15 - 30 - 50 degrees with no introduced sensory delays. Figure 2 (upper) shows the output potential of the second trajectory, and Figure 2 (lower) shows the two trajectories in polar coordinates. Polar coordinate representation was chosen because it corresponds to the actual movement of the robot from its egocentric perspective. Several experiments were made to compare the effect of changing heading direction with no cue delay, with a delay in the proprioceptive cue, and with a delay in the visual cue. In every experiment, a delay in the proprioceptive cue has less effect for generating the new heading direction. With equal cue delays, and with the neural field parameters constant for both cues, the experiments differed in the abruptness of changes in heading direction.

In a further experiment, two dimensional actions that resemble grasping of an object in a two-coordinate plane was simulated. The sensory models of the visual and the proprioceptive cues are based on the findings of Beers and colleagues [30], see also [37]. Three objects were located in different positions in space (Figure 3). We assume that when a subject has to grasp an object, he has to turn in the direction of the object. This means that the object is always located in front of the subject at the moment of grasping. This assumption is used to design the robot simulation. Figure 4 shows the results of the simulation: The response time of the output potential when there was no cue delay was compared with the results for a delay for each of the cues.

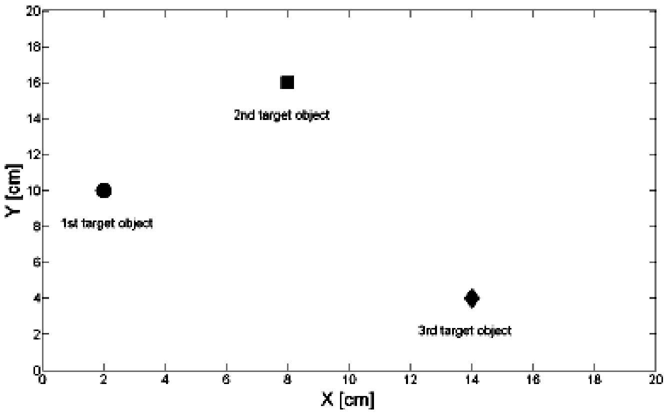


Fig. 3. Three target objects are located in different positions of a two dimensional plane. The simulation is started with the robot positioned at the origin pointing along the x-axis.

The results show that for proximal grasping, the proprioceptive cue has more effect on the output potential than the visual cue. As shown in figure 4, with the same delay time, the output potential takes relatively longer to be generated in the case of a delay for the proprioceptive cue.

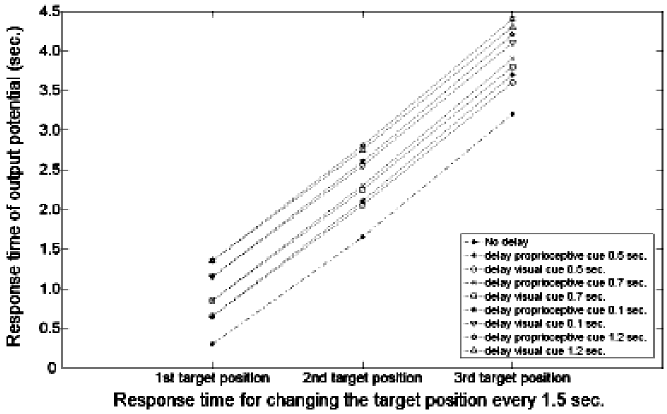


Fig. 4. Response time of output potential: without delay and with delays of 0.5, 0.7, 1, and 1.2 for each of the proprioceptive and visual cues.

Experimental data from [30] shows that the precision of movement is affected differently in terms of depth and azimuth motion by the visual and proprioceptive cues. The proprioceptive cue is more precise when the depth (distant goal) is targeted, and vision is more accurate in proximal (moment to moment) movements. To simulate this effect, the Gaussian ratio and amplitude of both cues were tuned to correspond to the variances in movement accuracy as found by Van Beers et al. [30]. Figure 5 shows the change of heading direction of the robot with tuned weighting parameters of the neural field model in the cases of no delay, delay for the visual cue, and delay for the proprioceptive cue. This result is in agreement with the experimental studies [30][37][38], and shows that DNF model approximates rightfully the precision of movement when the parameters for the two cues are directly borrowed from experiments with humans.

III. ROBOT EXPERIMENT FOR MODELING THE AUTISTIC BEHAVIOR.

For the robot experiment, an e-puck mobile robot was used. The e-puck is a two-wheel mobile robot that was originally developed at the Swiss Federal Institute of Technology (EPFL) [41]. The robot is equipped with a dsPIC processor, and with infrared sensors (IRs) that were used to obtain the information about the turning angle of the robot, which we will refer to as proprioceptive information. The obstacle-free space determined the possible direction of the robot for the next moment to moment movement. Vision was used to determine the target direction of the robot.

The experiment was divided into two parts: model validation and hypothesis testing. We need to validate the model on the real robot because the DNF model parameters might differ between computer simulation and the robot experiment.

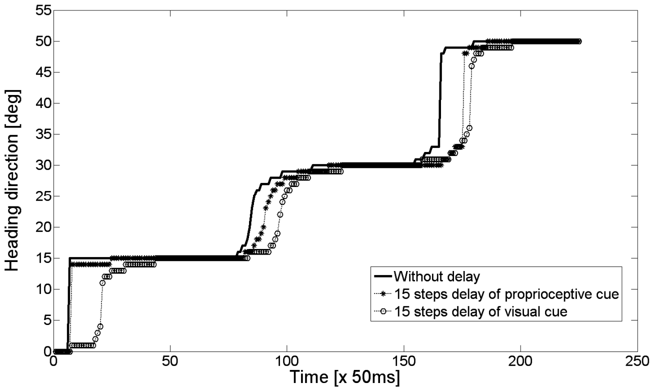


Fig. 5. Heading direction of the e-puck robot with and without delay when changing the target direction from 0 to 15 to 30 to 50 degrees. The 3 lines depict the change of heading direction after sensory integration without cue delays, and with a delay of 15 steps for each cue.

A. *Model validation*

To validate the model, we designed a task to search for a target hidden behind obstacles. The open arena contained several objects that served as obstacles (Figure 6). The heading direction was measured with respect to the initial position of the robot. (The positive x-axis was chosen as the zero degree direction, and the angle was measured counterclockwise). The target position was randomly changed each time after the time window for integration had passed.

The target searching task was chosen to not only set up the right values of each parameter of the neural field model, but also to test the sensors and the low-level control of the robot.

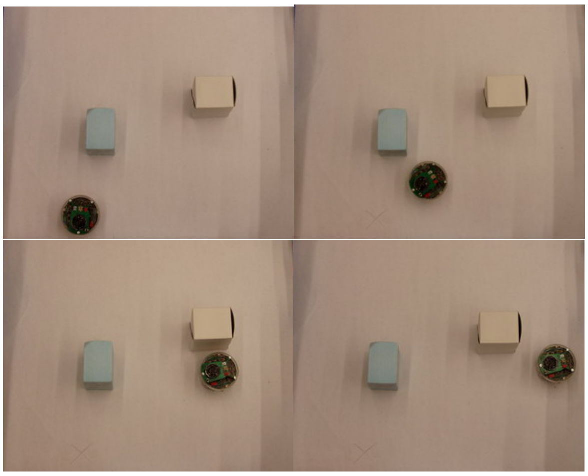


Fig. 6 An example of the path of an e-puck (round object) in an environment with arbitrary placed obstacles (blocks) is shown in the sequence of pictures from left to right and top to bottom.

Based on the initial parameter values from the simulation, the robot found the target and avoided the obstacles after 3-5 trials on average. Figure 6 shows an example of a path followed by a robot while performing this task. The results from a sample test are depicted in Figure 7.

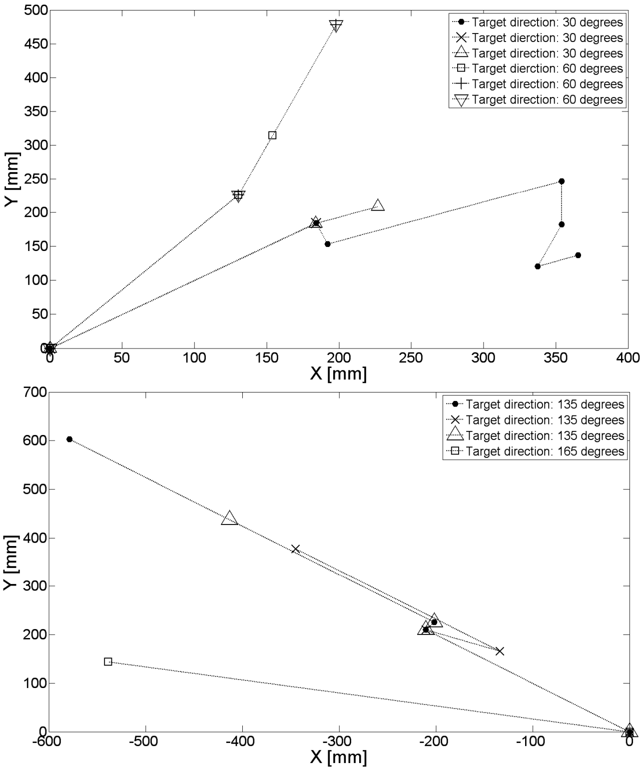


Fig. 7 Trajectories with target directions of: (upper) - 30 and 60 degrees, (lower) - 135 and 165 degrees, used to validate the model on a physical robot. The trajectories are all with no sensory cue delays.

These results show the movement of the robot when there is no delay added for the sensory cues. The time window was defined to be 550 ms, since the sensory processing for this robot and control program takes that time at present. The model is quite robust because e-puck can find any target. Moreover, the reliability of finding target in each target direction is similar.

B. *Hypothesis testing*

The dominance of proprioceptive over visual information for autistic children is well studied. Autistic subjects were reported to use visual information in order to determine the location of the target slot; however, they relied on proprioceptive information for reaching.

In robot setting we can assume that proprioceptive, or the visual information has been delayed so the simulated movement will depend on the better present cue. The influence of each sensory cue on the output behavior was tested after the experimental scenario was simplified by using only one obstacle in the arena, as shown in Figure 8.

With this simplification the influence of any artifact on the outcome of the experiment is excluded. In the absence of sensory cue delays, the robot can avoid the obstacle and reach the target (in the right upper corner in Figure 8).

When delay was applied to the proprioceptive or to the visual input, the robot took different trajectories. Depending on the distance of the obstacle and the speed of the robot, changing the delays had different effects. Figure 8 shows three sample trajectories of the robot: respectively, without delay, with delay for the proprioceptive sensory cue, and with delay for the visual cue.

Proprioceptive cue delay resulted in a collision between the robot and the obstacle. With a visual cue delay, the robot started to move in an arbitrary direction until the visual input was received, but nevertheless avoided the obstacle.

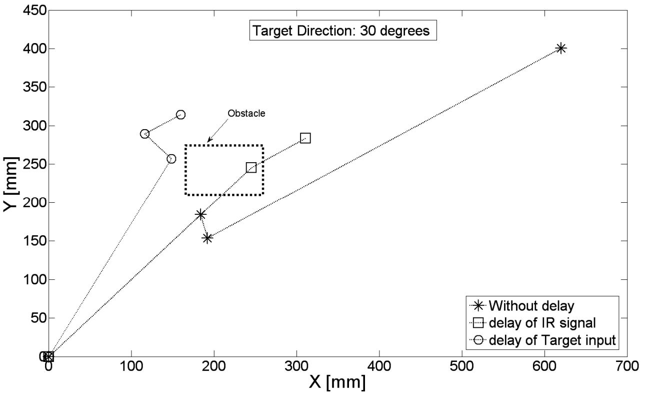


Fig. 8. Robot trajectories from sample experiment with no delay, proprioceptive cue delay, and visual cue delay.

This result could be compared with autistic and typical behavior. When both cues are timely integrated, a typical movement behavior occurs. When the visual cue is delayed, i.e. the robot relies more on the proprioceptive information, the proximal obstacle is avoided, but the handling (reaching to the distant object is interrupted. This may resemble the inability of autistic people to combine simple movements to a global complex behavior, as suggested by [15][16][17][18]. Masterton and Biederman [15] have shown that children with autism rely more on proprioceptive feedback than on visual feedback to modulate goal-directed motor actions. This includes reaching and placing objects under conditions that require adaptation to the displacement of a visual field by prisms. This finding might be indicative of a perceptual deficit resulting in poor visual control and poor visual sequential processing. When the proprioceptive information is delayed it results clumsiness of the robot, which collides with the proximal object. This is not comparable with autistic behavior, because autistic persons would easily deal with proximal objects.

IV. DISCUSSION

We applied the dynamic neural field model [1,2,3] to multimodal interaction of sensory cues obtained from a mobile robot in order to show the impact of different temporal aspects of the integration to the precision of movements. We speculated that temporally uncoordinated sensory integration might be a reason for the poor motor skills of patients with autism. Accordingly we made a simulation of 2D orientation behavior, and suggested that the results can be generalized for reaching to grasp movement that is performed in three dimensional spaces.

In particular, we investigated different temporal aspects of multisensory integration on the motor behavior of a robot, namely the effect of the size of the integration window and of delays for the different sensory cues. The DNF model was used to guide the robot movements, because this model contains two parameters which, as we have shown, can simulate the effects of the two temporal parameters: the influence of the interaction window and the delay in the sensory cues. The interaction window simulates the time for relaxation of system dynamics to the next fixed point, i.e. it isolates moment to moment multisensory integration. Using this property, we can delay recognition of each of the sensory cues and keep the integration within the span of the behavioral window.

The results show that a proprioceptive cue delay has less effect on close interactions, while a visual cue delay has less impact on distant target-finding. It is well known that autistic people are heavily reliant on proximal information, which in this experimental setting is the proprioceptive sensory information. Therefore distant grasping will be performed properly in general, except if it requires a combination of proximal and distant sensory information, as in the case of proximal obstacle.

The DNF model requires a certain time to generate output. When there were three successive direction changes, the outputs were different when the same period of delay was added for each cue (a single cue per trial). Implementing the model on the physical robot showed that sensory integration with the DNF model provides realistic behavior except that the length of the sensory integration window has to be tuned according to the restrictions of the processing capacity of this robot. The DNF model ensures human-like decision making and smooth motion when different external stimuli are present. However, the unreliable sensory information can result in totally different behavioral solutions when the robot starts from the same starting point in the same arena. Unrepeatable behavior may be caused by detection failure of the sensors or imprecise tuning of the parameters of the DNF model. The infrared sensors of the e-puck robot are sometimes too sensitive to detect the obstacles in the environment, and sometimes they cannot detect anything when the robot is too close to the obstacle. Moreover, measurement delays in feedback systems, as discussed in for instance [39][40] tend to cause oscillations and can be as well the reason for the unpredictable robot behavior.

This results in either the robot departing from the natural path or colliding with an obstacle. To fulfill our ambition of simulating the sensory integration process of autistic people we need a more advanced platform, and we are in the process of purchasing such. However, the results obtained with the current restrictions are very promising.

Our initial hypothesis was that bad timing in sensory integration causes poor motor performance in children with autism. Leary and Hill [4] argued that motor deficits of autism cannot be merely peripheral, but are central to the development of children with autism, and that they have significant impact on the development of higher cognitive atypical behaviors that include unusual sensory or motor behaviors, and also on social and communicative differences.

In summary, our experiments show that the impact of temporal aspects of sensory integration on the precision of movement is concordant with behavioral studies of sensory integrative dysfunction and autism. Specifically, the simulation predicts that distant grasping will be performed properly by autistic people in general, except if it requires a combination of proximal and distant sensory information, as in the case of proximal obstacles. We aim to extend our integration model to robot simulation of autistic and non-autistic grasping behavior, and to use it in games for behavioral training of autistic children**.**

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