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Robotic Set-Up to Quantify Hand-Eye Behavior in Motor Execution and Learning of Children with Autism Spectrum Disorder

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Abstract— **Autism spectrum disorder (ASD) is a multifaceted neurodevelopmental disorder characterized by a persistence of social and communication impairment, and restricted and repetitive behaviors. However, motor disorders have also been described, but not objectively assessed. Most studies showed inefficient eye-hand coordination and motor learning in children with ASD; in other experiments, mechanisms of acquisition of internal models in self-generated movements appeared to be normal in autism.**

In this framework, we have developed a robotic protocol, recording gaze and hand data during upper limb tasks, in which a haptic pen-like handle is moved along specific trajectories displayed on the screen. The protocol includes trials of reaching under a perturbing force field and catching moving targets, with or without visual availability of the whole path. We acquired 16 typically-developing scholar-age children and one child with ASD as a case study.

Speed-accuracy tradeoff, motor performance, and gaze-hand spatial coordination have been evaluated. Compared to typically developing peers, in the force field sequence, the child with ASD showed an intact but delayed learning, and more variable gaze-hand patterns. In the catching trials, he showed less efficient movements, but an intact capability of exploiting the available a-priori plan.

The proposed protocol represents a powerful tool, easily tunable, for quantitative (longitudinal) assessment, and for subject-tailored training in ASD.

I. Introduction

Autism spectrum disorder (ASD) is a multifaceted neurodevelopmental disorder characterized by a persistence of social impairment, communication abnormalities, and restricted and repetitive behaviors. Although it is not included in the diagnostic criteria, it is relevant to acknowledge the role of motor impairment associated with ASD. Deficiencies in motor coordination, such as hand-eye behavior, may have a significant impact on daily life activities. Indeed, up to 80% of children with autism show motor anomalies which are highly correlated with the severity of social impairment [1]. Motor signs include eye-movement abnormalities, deficits in fine and gross motor skills, in balance and coordination, in motor learning, and in tracking of moving targets [2], [3], [4],[5]. Moreover, ASD neural and circuit substrates remain mostly not understood. Abnormalities at the cerebellum level are among the most consistently reported brain differences in autism [6]. Despite literature evidences for cerebellar involvement in ASD, it remains unclear which changes in cerebellar functions have a significant behavioral impact. Controversial results are reported in the scientific literature. Larson and colleagues [7] found that children with autism improved their performances through formation of predictive internal models, with learning rates comparable to their typically developing peers. They speculated that, given the developmental context of autism, compensatory mechanisms might exist leading to normal adaptation despite the cerebellar lesions occurring early in brain development. On the other side, other studies showed a delayed learning of novel motor skills in ASD children [8], [9].

Patients with ASD show deficits in execution of motor actions compared to typically developing peers, and they can be more variable in their motor performances, indicating difficulties in maintaining performance consistency. It has been hypothesized that bad timing in sensory integration causes poor motor performance in children with ASD [4]. Hence, perceptually challenging tasks that require smooth integration of visual and proprioceptive information could result in poor quality of motor performance. Indeed, the dynamic aspects of integration of multisensory input influences the forming of coherent perception, planning, and coordination of action. In the clinical practice, these sensory-motor deficits have been mostly assessed by using clinical observation and self-report questionnaires [10]. The ability to non-invasively and objectively map developmental course of ASD, probing a sensitive marker such as hand-eye motor performance, would prove an invaluable contribution for assessing the response to intervention, and may even serve as a potential early indicator for the disorder [11], [12]. Little empirical research has directly examined the interaction between hand and eye actions in children with ASD, by means of quantitative, ad-hoc robotic devices.

Given the intrinsic appeal of technology to children with ASD, Information Technology devices can be exploited and

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easily adapted, allowing objective longitudinal assessment and tailored exercises, able to drive attention and keep motivation on sensorimotor tasks.

In this framework, we developed an experimental set-up able to provide integrated information between gaze and fine hand movement mediated by a robotic 3D printed pen-like handle at upper limb level. The experimental protocol has been designed to target specific ASD marker skills with two upper limb tasks, and in particular: i) a sequence of reaching trials with a perturbing force field, able to shed light on motor learning, variability in motor performance, gaze-motor coordination, eye-movement abnormalities, fine motor skills; ii) catching a target that moves along a pathway, able to shed light on planning and execution of motor actions, gaze-motor coordination, eye-movement abnormalities, fine motor skills. Within this work, the set-up and protocol validation on a cohort of Typically-Developing (TD) children has been performed, along with the definition of synthetic indexes able to describe the spatial and time features of the task sequences, both for hand and gaze behaviors. Reference values of TD children have been be extracted. In addition, the protocol was tested on a pilot child with ASD, as proof-of-concept and feasibility demonstration [13].

The proposed set-up and protocol (or its ad-hoc variations) might be used both for quantitative (longitudinal) assessment and for subject-tailored competence training. Indeed, it could support children with ASD to enhance motor skills related to hand-eye coordination, by actively engaging them in order to reach their learning potential, while at the same time measuring sensitive parameters, and their longitudinal evolution.

II. Material and Methods

A. Participants

Sixteen TD children aged between 8 and 10 years (7 females, 9 males; 13 right-handed, 3 left-handed) were enrolled for this study. A child with ASD, 8 years old, right-handed, male (sub-test visuo-motor Precision-NEPSY II, total score: 10; reference normative range: 7-13) was recruited. Experiments were conducted with the approval of the local ethical committee following the Declaration of Helsinki, and all the participants' legal guardians gave their informed written consent prior to the children's participation.

B. Experimental set-up

The experimental set-up was composed by a table-mounted screen Eye Tracker T60 (Tobii), with a sampling frequency of 60 Hz and 1280x1024 pixels screen, an haptic robotic manipulandum (Phantom Omni, Sensable-Geomagic) with a 3D printed pen-like handle, with a sampling frequency of 1 kHz, and a control pc where a self-developed control algorithm runs in a Visual C++ environment (Figure 1). The eye tracker requires a subject-specific calibration (looking at a circle changing 9 predefined positions within the screen) that lasts about 30 seconds. Before to perform specific tasks, all participants performed a familiarization session exploring the screen with their gaze, and moving the robot handle on the working space. On the screen, online visual feedback of gaze, and robot handle position projected on the screen was available.

Figure 1. Experimental set-up. Eye tracker (center), Phantom Omni with pen-like handle (left)

C. Task 1

In Task 1, a diagonal straight path had to be followed by moving the robot end-effector from a "start" square to an "end" square target without exiting from the path boundaries. The task has been designed as a classic learning paradigm [14] where the first 9 trials were carried out without perturbation, then 30 trials ("acquisition") enabling a force perpendicular to the path line, gradually increasing its intensity from 0N to 3N along the desired path (activated when the end-effector goes out from the "start" square), and then the last 9 extinction trials in which there was again no perturbing force. The subject was not aware about the change of the dynamic environment along trials. The subject was provided with the online visual feedback only about the end-effector actual position (and not about gaze position). Both gaze and robot positions were recorded. This task aimed at investigating the motor learning capability, including acquisition and extinction phases, and hand-gaze patterns.

D. Task 2

In Task 2, a little squared target moved on the screen following a curvilinear predefined path. The selected path correspond to the a digitalized version of the visuo-motor precision sub-task of the NEPSY-II protocol, usually administered in clinics with paper-pencil and observation-based [15]. The task was composed by three trials: (A) the moving target (a red square) was displayed, and the participant had to catch it with the pen-like robot handle whose feedback was represented on the screen as a violet square; (B) the moving target was displayed on the screen, but the complete path the square followed was as well displayed on the screen, and the participant was asked to behave like in A); (C) the subject was asked to track the same path at a self-paced velocity (no moving target was displayed). In all trials, the subject was provided with the online visual feedback only about the end-effector position on the screen. Both gaze and robot positions were recorded. This task aimed at investigating

planning and execution of motor actions, and hand-gaze patterns.

E. Data Analysis

For Task 1, for each trial, the product between the executed path length (*pathL*) and the actual duration (*T*) was computed; a more precise spatial execution (shorter path length) can be due to a slow movement (higher duration); the tradeoff between these two factors is taken into consideration. Specifically *pathL* is the ratio between the actual path length and the line length from the starting to the end-point. Then, an index describing the overlap between gaze and hand patterns has been computed, by calculating, for each trial, the mean 2D distance between gaze and end-effector positions (*hand-gaze dist*).

For Task 2, four indices have been derived, and in particular: i) digital evaluation of NEPSY-II visuo-motor precision sub-task (trial C); the score has been computed as for the clinical paper-pencil test [15]; ii) for Trials A and B separately, motor performance index has been computed as the product between *time_on_target* and the *normalized_vel*, where *time_on_target* is the relative time the robot handle feedback has been over or close (less than 15 pixels) to the moving target, and *normalized_vel* is the velocity of the robot handle in trial A (or B) over the velocity in trial C taken as common reference; iii) for Trials A and B separately, fine motor skills have been evaluated as movement jerk of A (or B) trial over jerk of C trial [16], and iv) for Trials A and B separately, gaze-motor coordination has been evaluated as 2D distance, averaged across time samples, between gaze and end-effector positions.

Within the TD group, the median and 25-75 percentiles across subjects were computed, for each of the 48 trials of Task 1, and for each of the three trials of Task 2. Paired-samples Mann-Whitney U test was applied to compare Trial A and B indexes.

III. RESULTS

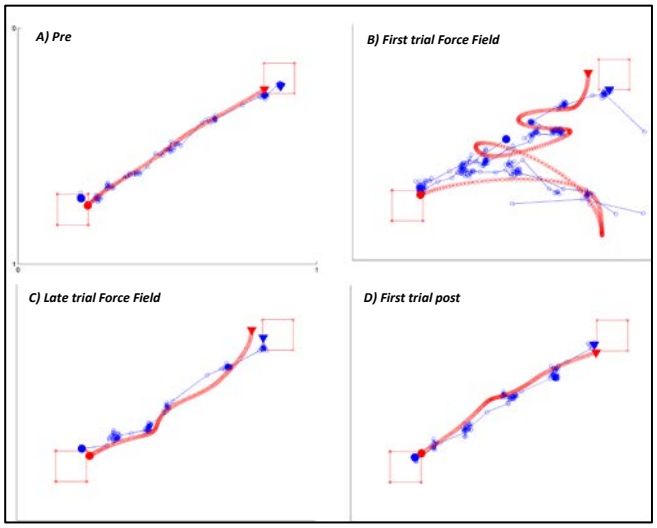
Each child performed the whole protocol, without fatigue, on average in 20 minutes.

A. Task 1 – motor learning: force field reaching

Figure 2 depicts a representative result obtained in Task 1. The gaze pattern is characterized by point clusters, representing fixation events along the path tracked by the end-effector. In the "pre" unperturbed condition the path was almost straight and homogenous (Figure 2, panel A). When unexpected force was imposed, the deviation was quite high, and delayed feedback mechanisms were actuated to counteract the force and go back on the desired path (Figure 2, panel B). Since the same force was applied for multiple trials in a row, the system learned and predictively compensated the disturbance, i.e., at late acquisition (Figure 1, panel C). Finally, when the force was unexpectedly switched off, the compensation still acted leading to a slight path curvature on the opposite side; however the extinction rapidly occurred going back to the baseline performance (Figure 2, panel D).

Figure 3 reports *pathL·T*. The TD group showed a stable behavior during baseline, a very rapid learning trend during the force field, recovering soon values closed to baseline, then during the last extinction trials a slight performance improvement was detectable in the first 2 trials, and then stable performance continued for the last seven trials at a level even better than in the baseline trials.

Figure 2. Gaze (blue) and End-Effector (red) 2D trajectories during Task 1 performed by one TD child (S03). Four trials are reported: baseline (5th), the first one when force field is enabled (10th), at the late acquisition (24th), the first one when force field is disabled again (40th).



The ASD child showed worse performance at the beginning of the force field phase, he took almost 9 trials to learn to anticipate the perturbation and go back to stable baseline values. The extinction phase was as his TD peers. However, in a few sporadic trials his performance was worse (slower and/or more curved path). A different behavior in terms of *pathL·T* of the child with ASD with respect to the TD peers (value outside the IQR of the TD population) was evident slightly for trials 1, 2, 8 (baseline phase, randomly), strongly from trial 11 to 18 except 15 (early acquisition phase, almost in a row), 29, 34, 38, 39 (late acquisition phase), and 48 (late extinction phase).

Figure 3. *pathL·T* in Task 1 (9 trials baseline, 30 trials with force field, 9 trials unperturbed again). In black median and 25-75 percentiles of TD group. In gray, data of the child with ASD.

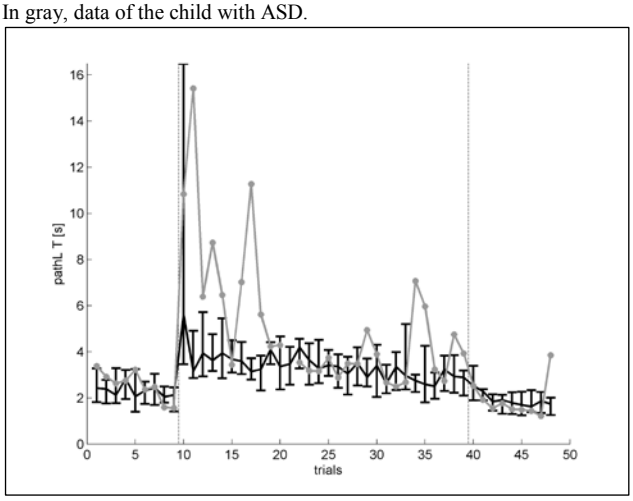


Figure 4. *Hand-gaze dist* in Task 1 (9 trials baseline, 30 trials with force field, 9 trials unperturbed again). In black median and 25-75 percentiles of TD group. In gray, data of the child with ASD; trials 18 and 21: not available gaze data.

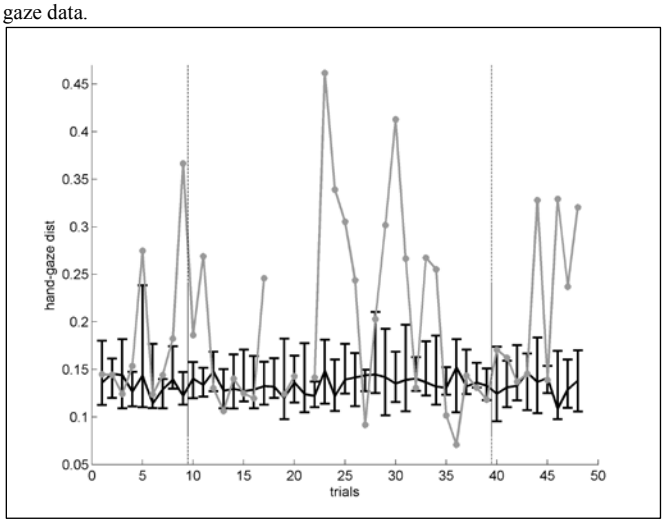


Figure 4 reports *hand-gaze dist.* The TD children showed a consistent stable hand-gaze spatial coupling along all trials regardless which path they fulfilled. The ASD child showed a much more variable behavior: gaze movements were not always consistent with the executed hand path. A different behavior in terms of *hand-gaze dist* of the child with ASD with respect to the TD peers (value outside the IQR of the TD population) was evident for 24 trials, regardless the sequence phase. In 21 of these 24 trials, the values were higher than the TD ranges, whereas in the other 3 trials the values were lower. Thus, overall, the overlap between hand and gaze paths was reduced with respect to peers (higher average distance between hand and gaze positions).

B. Task 2 – motor execution and planning: catching a moving target

Figure 5 represents an example of A and B trials of Task 2 carried out by a TD child. It is evident that the a-priori knowledge of the path (Trial B) yields to a smoother performance of the end-effector path; this consequently yields to a smoother gaze trajectory, which partially matches the desired target path and partially the actual end-effector path.

Table I reports the four indices of Task 2 for each subject, the corresponding median, and 25-75 percentiles across the 15 TD subjects (S01 data were not valid since failure of eye tracker recording). In TD population, Trials A and B resulted to be significantly different in terms of motor performance index (p-value=0.013) and jerk values (p-value=0.025). Trial B was better performed and in a slightly smother way than trial A, whereas, average hand-gaze distance was comparable between Trials A and B, even in Trial B the gaze-hand overlap was higher and less variable across subjects. As reported in the last row of Table I, the child with ASD showed an overall worse motor performance, but still better in trial B than in trial A. His jerk values were comparable with respect to TD ones, still with an intra-subject difference between trials A and B (smoother in B than in A). Finally, the overlap between hand and gaze paths was reduced with respect to peers (higher average distance between hand and gaze positions in both trials A and B).

Figure 5. 2D trajectories (on screen sizes) of the Gaze (blue) and of the End-Effector of the robot handle (red), during Trials A and B of Task 2, performed by one TD child (S08). In gray, the target path.

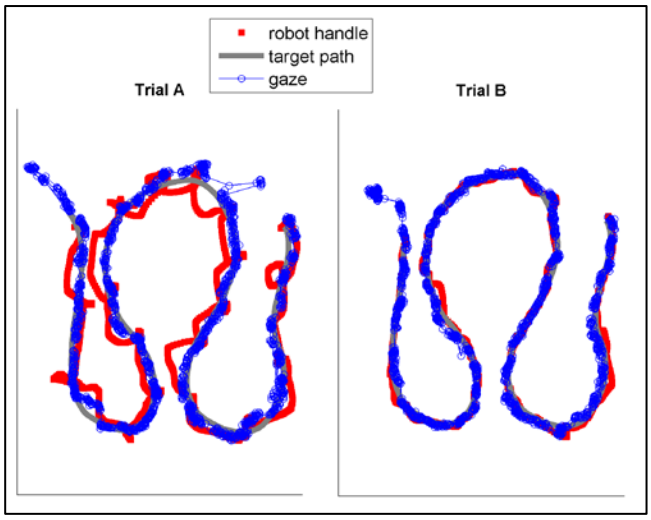


TABLE I. INDEXES OF TASK 2 FOR EACH SUBJECT, MEDIAN AND INTER-QUARTILE RANGES (IQR= 75-25 PERCENTILES) ACROSS 15 TD SUBJECTS (S02-S016); LAST ROW REPORTS VALUES FOR THE CHILD WITH ASD

	Dig NEPSY -II	*Motor performance*		*Jerk*		*Hand-gaze dist [norm]*	
	C	***A***	***B***	***A***	***B***	***A***	***B***
S02	11	0..23	0.25	1.17	0.98	0.116	0.113
S03	9	0.19	0.20	1.13	1.05	0.028	0.031
S04	7	0.38	0.38	1.57	1.09	0.1250	0.041
S05	7	0.26	0.13	1.22	1.13	0.031	0.042
S06	6	0.23	0.32	1.59	0.96	0,032	0,032
S07	7	0.15	0.34	1.32	1.02	0,041	0,028
S08	8	0.22	0.42	1.53	1.31	0,051	0,034
S09	7	0.24	0.26	1.36	1.30	0,032	0,040
S10	8	0.32	0.48	1.93	1.92	0,030	0,027
S11	7	0.34	0.30	1.17	1.09	0,042	0,033
S12	9	0.29	0.43	1.85	1.09	0,030	0,024
S13	7	0.07	0.34	1.45	1.85	0,04	0,023
S14	11	0.23	0.28	1.27	0.96	0,028	0,0254
S15	6	0.12	0.24	1.02	0.95	0,2528	0,138
S16	6	0.41	0.47	1.80	1.87	0,1638	0,049
Median (IQR)	7 (1.5)	0.23 (0.1)	0.32 (0.14)	1.36 (0.39)	1.09 (0.31)	0,040 (0,053)	0,033 (0,014)
ASD child	6	0.10	0.17	1.22	1.12	0,057	0,089

IV. Discussion

Motor abnormalities and clumsiness are relevant features of ASD disorders, well-known since the earliest clinical descriptions [5]. Quantitative markers of motor learning and motor performance, describing the hand-eye motor control, would be important for assessment and evolution tracking of ASD. Moreover, quantitative evaluation of motor performances might be of the utmost importance since motor impairments are predictive of ASD outcome (e.g., head control and ability to weight bear on arms in prone position, and coordination of movements when walking) [17].

Our study, through Task 1, shows a clear learning trend of the TD children with an effective counteraction able to predicatively contrast the environmental disturbance; high inter subject variability was evident in the first trial of the force field phase. The after-effects were quite reduced, and recovered in a couple of trials. The child with ASD showed a longer adaptation phase, suggesting that the ability to learn from sensory prediction errors and acquisition of internal models is delayed, but intact. However, the ASD child was more variable in his motor performances, indicating more difficulties in maintaining performance consistency. In line with our previous data [18], the gaze pattern of the child with ASD was less consistent with the hand pattern compared to the TD children.

We thus support the hypothesis that bad timing in sensory integration, of visual and haptic cues, causes poorer motor performance and delayed learning in children with ASD [4]. The timing, strictly correlated to prediction and adaptation, is one of the crucial aspect managed by the cerebellum [19].

For what is concerning Task 2, the results obtained in the score of the digitalized NEPSY-II visuo-motor coordination sub-task yielded to the expected results, with a median performance of 7 for TD group, which correspond to no functional deterioration. The child with ASD obtained a score of 6, within the TD bandwidth, in line with the outcome of the same paper-pencil task, in which he got a score of 10, within the reference normative range of the TD children (between 7 and 13). Well distinguishable behaviors can be appreciated between trials A and B. Indeed, trial B (where trajectory was shown) yielded better results in terms of jerk and motor performance. These results support the hypothesis that the availability of the whole path during the task allowed a continuous motor planning with stronger feedforward components. The child with ASD behaved similarly to the TD control group, even if with a slightly worse performance; still he is able to take advantage of the availability of the whole motor plan. As for Task 1, for the child with ASD, the gaze movement was not always consistent with the executed hand path.

We thus support the hypothesis that simple motor planning is intact but that the use feedback is diminished, affecting the quality of motor performance.

As argued by Leary and Hill [5], autism motor deficits cannot be merely peripheral, but 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.

Abnormalities at the cerebellum level are among the most consistently reported brain differences in autism [6]. Long-term depression (LTD) has been put forward as impaired functional/cellular processes in ASD, which sub-serves synaptic plasticity in the cerebellum, and it is critical to learning and refining behavioral errors [20]–[22]. Such functional abnormalities, together with structural alterations (e.g. loss of Purkinje cells [23]) could affect not only motor processes, but also cognitive ones [6], [24], consistently with the evidences about the cerebellar role in cognition and emotion. In addition, one of the most robust findings in ASD is the atypical processing for the ability to update target velocity and trajectory, predict future target positions and integrate these signals with other actions, such as eye-hand coupled actions. Impaired motion tracking may also help to explain the widely-documented visuo-motor impairments in ASD [2], [3], [11], [25]–[27]. Characterizing ocular motor abnormalities in ASD may provide insight into the functional integrity of brain networks across development, and assist our understanding of visual and social attention in ASD [28]–[30].

Very recently, a first study with a digitized handwriting task has been conducted, to figure out objective descriptive measures [31]. They showed scholar-aged children with ASD performed less smooth movements and with higher spatial and velocity variability than aged-matched TD subjects. Such impairments correlated with clinical symptom severity and attention skills [31]. The set-up developed within the presented study allows designing handwriting (rehabilitative) tasks, during which real-time feedback based on gaze-attention signals or corrective force-guidance signals can be provided by visual or haptic cues. In general, it is suitable for subject-tailored training treatments.
Furthermore, the interface parameters can be adjusted in order to make the tasks feasible even for pre-schoolchildren, challenging the protocol as a quantitative tool for early diagnosis.

As a conclusion, this work develops a powerful tool, able to detect sensitive markers of hand-eye behaviors, such as learning rate and effectiveness, and performance indexes. Consistent outcomes emerged within the TD group, with indexes able to objectively describe the expected behaviors and define reference ranges. An experimental session has been conducted as a proof-of-concept and feasibility test, comparing a single subject — a child with ASD — with typically developing peers. Work underway will address the limitation of the present study. We are currently recruiting a significantly larger sample of children with ASD, with different degrees of severity and motor impairments.

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