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# Eye gaze performance for children with severe physical impairments using gaze-based assistive technology—A longitudinal study

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**ABSTRACT**
Gaze-based assistive technology (gaze-based AT) has the potential to provide children affected by severe physical impairments with opportunities for communication and activities. This study aimed to examine changes in eye gaze performance over time (time on task and accuracy) in children with severe physical impairments, without speaking ability, using gaze-based AT. A longitudinal study with a before and after design was conducted on 10 children (aged 1–15 years) with severe physical impairments, who were beginners to gaze-based AT at baseline. Thereafter, all children used the gaze-based AT in daily activities over the course of the study. *Compass* computer software was used to measure time on task and accuracy with eye selection of targets on screen, and tests were performed with the children at baseline, after 5 months, 9–11 months, and after 15–20 months. Findings showed that the children improved in time on task after 5 months and became more accurate in selecting targets after 15–20 months. This study indicates that these children with severe physical impairments, who were unable to speak, could improve in eye gaze performance. However, the children needed time to practice on a long-term basis to acquire skills needed to develop fast and accurate eye gaze performance.

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**KEYWORDS**
assistive devices; computer access; physical disability

## Introduction

Some children with severe physical impairments also lack the ability to speak. They are commonly diagnosed as having cerebral palsy (Cans, 2000), and the severe motor impairment is often associated with concomitant cognitive impairment and limited performance in everyday activities (Kantak, Sullivan, & Burtner, 2008; Rosenbaum et al., 2007). These children do not have control over their body movements and are therefore dependent on assistance in all activities, including communication, eating, and playing (Cans, 2000; Østensjø, Carlberg, & Vøllestad, 2005). Eye movements may be the only movements they can control voluntarily. For that reason, assistive technology (AT) based on a computer controlled by their eyes (gaze-based AT) may be the only option for operating a computer for those having such severe physical impairments (Majaranta & Donegan, 2012). The idea is that the eye gaze device replaces the keyboard and mouse as the interface method (Lin, Yang, Lay, & Yang, 2011; Majaranta et al., 2012). By using their eyes, children with severe physical impairments can control the computer and gain access to communication and activities, such as playing games and music (Lariviere, 2014). In this study, AT is defined according to the definition used by the International Organization for Standardization (2011), which states that "an assistive product is any product (including devices, equipment, instruments and software), especially produced or generally available, used by or for persons with disability, for participation, to protect, support, train, measure or substitute for body functions/structures and activities, or to prevent impairments, activity limitations or participation restrictions." Thus, gaze-based AT may provide opportunities for children to communicate and perform a range of activities, even if they have severe impairment.

Gaze-based AT is an underutilized AT, and even though it is available in Sweden and other countries worldwide, few children with profound impairments currently have access to it. It is possible that stakeholders may consider the AT to be expensive, or because of doubt over whether non-speaking children with severe physical impairments and cognitive impairments can control a computer with their eyes. Even though it is natural for humans to consciously control gaze and explore by directing their eyes to objects, it is a challenging task to learn how to use the eyes to control objects on a computer screen (Donegan, 2012b; Heikkilää & Ovaska, 2012; Skovsgaard, Räihä, & Tall, 2012). Novice users will not have any previous experience of controlling objects with eye gaze to relate to, as the natural way of using eye gaze is for perception (Hansen & Aoki, 2011). Using gaze-based AT requires control of eye movements (Mulvey, 2012), as well as the ability to switch between using gaze for exploration and for selection of objects (Hansen & Aoki, 2011). Case studies have shown that

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interacting with the computer by pointing to and selecting items with eye gaze, leads to tiredness and exhaustion during initial use for novice users with severe physical impairment (Donegan, 2012b; Najafi, Friday, & Robertson, 2008).

Positive outcomes from the use of gaze-based AT in daily life for adults with severe motor impairment have been reported in several studies (Caligari, Godi, Guglielmetti, Franchignoni, & Nardone, 2013; Caltenco, Breidegard, Jönsson, & Andreasen Struijk, 2012; Spataro, Ciriacono, Manno, & La Bella, 2014). Although some of these studies have promising results, research on gaze-based AT that involves children with profound impairments without speaking abilities is sparse. A case study showed that an eye gaze device could be used to perform cognitive tasks by two girls with Rett syndrome (Baptista, Mercadante, Macedo, & Schwartzman, 2006). User trials have shown that gaze-based AT can be adapted to meet the requirements of children with physical impairments with accompanying difficulties (Donegan et al., 2009). A case study of van Niekerk and Tönsing (2015) found that gaze-based AT could be used by children with cerebral palsy, even though it was not utilized fully in daily activities due to a lack of support. On the other hand, Man and Wong (2007) and Dhas, Samuel, and Manigandan (2014) found in case studies that eye gaze devices were unsuitable due to there being too many involuntary movements in children with cerebral palsy. Amantis et al. (2011) found longer time and less accuracy in eye gaze performance for children with cerebral palsy compared to children without impairments and concluded that there was a need to analyze usability in respect to children with impairments. The importance of ongoing training and support, and of assessing improvements in eye gaze performance over time has also been highlighted in case studies (Donegan, 2012b; Najafi et al., 2008).

In earlier studies, "learning curve" has been used to describe the learning over time of a new AT (Caltenco, Breidegard, & Andreasen Struijk, 2014; Jenko et al., 2010). "Learning curve" is usually created to display improvements in performance over time with a device and concerns the amount of practice a novice user needs to overcome to gain proficiency in using a device (Nielsen, 1993). Research indicates that children with profound impairments may need several months or more than a year to learn the new skills needed to operate a new computer input device. For example, case studies indicate the need of practicing over several months before learning eye gaze control of smaller targets due to complexity of physical and visual difficulties (Donegan, 2012b; Donegan & Oosthuizen, 2006). Another study showed remaining problems in achieving sufficient operational skills after 1 year of use of an AT for communication (Salminen, Petrie, & Ryan, 2004). Therefore, there is a need to measure performance over longer periods than 1 year with children with complex impairments to capture improvements in performance. Furthermore, implementing gaze-based AT in daily life is time-consuming as several people in the child's immediate environment need support and guidance in the implementation process (van Niekerk & Tönsing, 2015). This in turn may have an impact on the child's opportunities to use the gaze-based AT in their everyday activities. This study is a part of a longitudinal project investigating gaze-based AT for children with severe physical impairments. In a forthcoming study the use of gaze-based AT in daily life is examined. The current study focuses on the children's capacity (performance capacity) to control the computer with their eye gaze. The performance capacity depends on physical and mental components and subjective experience of the doing (Kielhofner, 2008). Thus, the performance capacity in controlling a computer with eye gaze depends on their ability to control their eye movements, their ability to understand the task and the interaction with the computer, as well as their experience of using gaze-based AT in daily life. The mastery of new skills has been described to develop through the stages of acquisition, fluency, generalization, and adaptation of skills. Through practicing skills the learner acquires skills (becoming accurate but with slow performance) and then becomes more fluent in the performance (becoming accurate with sufficient speed) (Parker, Matthew, Burns, McMaster, & Shapiro, 2012). Generalization and adaptation of skills were not the focus in the present study. Thus, performance capacity may increase over time through practice and experience. The aim of this study was therefore to examine changes of eye gaze performance over time (time on task and accuracy) in children with severe physical impairments, without speaking ability, using gaze-based AT.

## Methods

A longitudinal study with an AB design was conducted on 10 children with severe physical impairments, without speaking ability, as they started to use gaze-based AT.

### *Participants*

The sample comprised of all children ($n$ = 10) who were referred to a multi-professional communication team (MPC team) at one regional pediatric center in Sweden during 2010–2013 requesting to participate in a gaze-based AT intervention (access to gaze-based AT, and access to services from MPC team). The children were between 1 and 15 years of age and were diagnosed with cerebral palsy ($n$ = 9), or cervical spinal cord injury ($n$ = 1). Table 1 shows the children's diagnosis, motor impairment, and associated impairments. The information was taken from the children's medical records. As Table 1 shows, the children had severe impairments in gross motor function, manual ability, and in communication ability. The children with cerebral palsy represented the lowest functional levels (IV-V) in the Gross Motor Function Classification System (Palisano et al., 1997), the Manual Ability Classification System (Eliasson et al., 2006), and the Communication Function Classification System (Hidecker et al., 2011). None of the 10 children could speak, and they used methods such as facial expressions and eye-pointing for augmentative and alternative communication (AAC). Some of the children also had single pictures or low- tech communication boards. Five children had unspecified cognitive impairments (Max, Adam, David, Lucas, Anna), whereas the cognitive level was unknown for two children (Daniel, Isaac), and three children were reported to have normal age-related cognition (Emma, Jacob, Marcus). However, this specific group of children is difficult to assess thoroughly because of their profound impairments, which is why complete assessments may not have been possible. It is known that such children commonly have varying cognitive profiles. Four

Table 1. Children's characteristics.

| Characteristics | Children (*n* = 10) |
|---|---|
| Sex | |
| Boys | 8 |
| Girls | 2 |
| Age *m* (*SD*) | 8.6 (4.6) |
| School | |
| Mainstream school, special class | 2 |
| Special school | 6 |
| Special preschool | 1 |
| Diagnosis | |
| CP dyskinetic | 4 |
| CP spastic diplegia | 2 |
| CP spastic tetraplegia | 3 |
| Cervical spinal cord injury | 1 |
| Gross motor function[a] (Gross Motor Function Classification System) | |
| Level IV | 4 |
| Level V | 5 |
| Manual ability[a] (Manual Ability Classification System) | |
| Level IV | 5 |
| Level V | 4 |
| Communication function[a] (Communication Function Classification System) | |
| Level IV | 7 |
| Level V | 2 |
| Cognition | |
| No impairment | 3 |
| Unspecified cognitive impairment | 5 |
| Unknown (not been possible to assess) | 2 |
| Vision | |
| Refractive error | 4 |
| Eye glasses (during gaze-based assistive technology interaction) | 1 |
| Alternating strabismus | 2 |
| Cerebral Visual Impairment | 1 |
| Hearing | |
| Hearing impairment (no need for hearing aid) | 2 |
| Epilepsy | 4 |

*Notes.* [a]Only applicable to children diagnosed with cerebral palsy. CP = Cerebral Palsy.

children had refractive errors of vision. For one child this was corrected with glasses, while the rest did not need glasses in front of the computer. Two children had alternating strabismus. All children in this study were beginners to gaze-based AT at the start of the study. Three of them had had access to gaze-based AT shortly before enrollment, but had not used it (or only sporadically), according to the local pediatric team and parents. All the children were highly dependent on assistance in everyday activities. The names used in this article are not the children's real names.

## *The gaze-based AT intervention*

The intervention consisted of access to a gaze-based AT in daily activities, and receiving services from the MPC team (for details, see section "Services in the Gaze-Based AT Intervention").

### *The gaze-based AT*

In the present study, nine children used the gaze-based AT Tobii C12, which has a 12″ screen and works optimally at a distance of 23.5″ (60 cm) from the eyes. One child used the gaze-based AT Tobii P10, which has a 15" screen with an optimal working distance of 20–28″ (50–71 cm) (Tobii Technology, 2013). Both devices have a built-in gaze device, are portable, and tolerate a range of eye head movement of 15.7 × 11.8 × 7.9 in (C12) or 12 × 6 × 8 in (P10). These devices need to track at least one eye when used. In both devices, the built-in camera reads with an accuracy of 0.8 degrees (C12), or 0.5 degrees (P10) of gaze estimation in the user's visual field. Selections of objects are made by fixating on the object during a pre-specified dwell time. Gaze calibration is a critical issue and is initially performed before usage. This is essential in order to obtain reliable results for the specific user during usage (Hansen & Majaranta, 2012). For a child with spasticity, the system needs to be flexible by allowing for involuntary head movements during interaction (Donegan, 2012b). In cases of strabismus, the system's function to accurately detect and track eye movements may be compromised.

### *Services in the gaze-based AT intervention*

The MPC team provided services (lasted 9–10 months) with the purpose of optimizing the learning, the use, and implementation of gaze-based AT in daily activities, in home and in school for the children (see Figure 1). The theoretical basis of the intervention is that regular training in skills (eye gaze performance) by using them in daily activities will optimize learning of these skills. For that reason services are provided in children's everyday life in which skills and activities are performed (Kemmis & Dunn, 1996). The services in the intervention program are built upon collaborative consultation and direct support (Dettmer, Dyck, & Thurston, 2002; Kemmis & Dunn, 1996; Villeneuve, 2009) and based upon the same research-based key elements (increased knowledge among teachers, collaboration between key persons, child's preferences for use, goal setting) as described in an earlier study (Borgestig, Falkmer, & Hemmingsson, 2013). The format of services in the gaze-based AT intervention was (a) two introduction days for the child, parents and teacher (for education and adaptation of the gaze-based AT for the child's needs, training in gaze control for the child); (b) three consultative group meetings (parents meet parents 1 × 6 hours, teachers meet teachers 2 × 6 hours; for exchange of experiences, adaptations of gaze-based AT); (c) a group meeting for children when they use the gaze-based AT (1 × 4 hours, for training and play); and (d) three individual meetings for all stake holders for each child (goal formulation for use in daily activities, developing strategies for use, and goal evaluation). Each child was also provided with direct or indirect support (including parents, teachers, assistants) at home or/and in school (five occasions) (support in gaze control and gaze-based AT use in daily activities). All professionals in the MPC team (occupational therapist, language and speech therapist, technician, special teacher) were well trained in the use and adaptation of gaze-based AT, and had knowledge of child disability. No new concurrent interventions were provided to the children during the gaze-based AT intervention.

## *Instruments*

*Compass 2.0 Software for Access Assessment* (Koester, Simpson, Spaeth, & LoPresti, 2007) is computer software that is used to measure the client's skills in computer

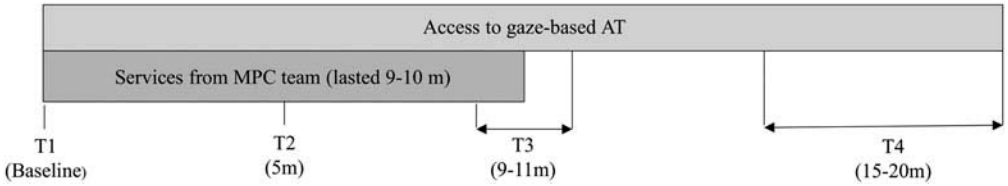


**Figure 1.** Time points (T1–T4) for data collection with Compass (in months). MPC = multi-professional communication team.

interaction. It is designed to help AT professionals perform computer input evaluations. The Aim test in Compass measures the user's ability to control the mouse pointer and was used to measure the children's time on task and accuracy in eye gaze performance of gaze-based AT. The task was to select targets (three different animals) that were randomly presented in different places on the screen, one at a time. Each target was presented at one of three distances to the mouse cursor; one tenth or two tenths of the screen width (short or medium distance), or the distance of half of the screen (long distance). The Aim test has high test-retest reliability (intraclass correlation coefficient 0.98) (Koester et al., 2007), high construct validity (Koester, LoPresti, & Simpson, 2011), and good internal consistency (Cronbach α of 0.77) (Koester et al., 2007). Each single test was set up to include 12 targets that had the maximum possible size in the program, each target with a size of 100 × 100 pixels. Selection was carried out by gazing at the target for longer than the pre-specified dwell time of one second. After selection, there was a blank period of 2 seconds before the next target was presented. *Time on task* is the required time from which a target is presented until selection is made by the child. The maximum time for selection was set to 30 seconds (by default in the test), and failure to fixate on a target for selection within this threshold equated to a missing target. *Accuracy* is classified according to whether each target is selected or missed within the threshold. The threshold of 30 seconds was assumed to be long enough to give the children an opportunity to select a target even if they had difficulties with eye selection, but not long enough to bore the children if they were unable to fixate on a target. This generated a total time limit of about 6 minutes for each test, which was considered to be a feasible amount of time for children of different ages to engage in the task.

## Procedures

At baseline (T1), seven children were provided with gaze-based AT. In the period following baseline, the MPC team at the pediatric center supported all 10 children, their parents, and school personnel, in order to optimize the use of gaze-based AT in daily activities. The support periods were tailored to each child, and lasted between 9 and 10 months. Data from Compass were collected once for each of the 10 included children at each of the four time points; at baseline (T1), at 5 months (T2), between 9–11 months (T3), and between 15–20 months (T4) from baseline. The time intervals for the T3 and T4 data collections were required to allow for extraordinary events, such as long hospital stays due to surgery, or long breaks from school, such as the summer or Christmas breaks.

Having access to gaze-based AT and support from the MPC team, all 10 children started to use the AT in daily life. Nine children used the system for at least every second day across time points T2–T4, whereas David used it for 1–2 days a week across these time points. Lucas did not use the gaze-based AT at T2 due to seating problems. Most children had a duration of approximately 25–60 minutes per user day (mean) across the study.

The Aim task in Compass was chosen as it was considered to be cognitively undemanding for the children and therefore not likely to be related to age. The Compass assessment situation was set up as a standardized environment in the children's schools, at home, or at the pediatric center. The assessment situation was individualized and optimized to support each child to complete the test to the best of their ability. The gaze-based AT was positioned at a distance of about 60 cm from the child's eyes. The child was then repositioned to the optimal horizontal and height positioning for eye tracking by using the track status viewer on the Tobii device. This procedure resulted in distances of 55–59 cm between the children's eyes and the screen. Gaze calibration (the user looks at on-screen targets so the system can estimate the individual gaze) and improvements of calibration results was performed by the researcher to find the best user profile. All children, including children with refractive error or strabismus, showed that they were able to accurately gaze at targets in the test. After one initial trial, the test was administered three times when possible, resulting in a maximum of 36 presented targets (12 × 3). At baseline the youngest participant was only 10 months and it was decided to use a maximum of 32 targets (8 targets × 4 tests) for this specific child. During assessments, the children were encouraged to hit the targets as fast as possible. Breaks were offered when needed between the tests.

## Data analyses

Statistical analyses were performed on the data for time on task, and accuracy for the sample as a whole. To test for normal distribution of the variable time on task, the Kolmogorov-Smirnov test (Field, 2013) was used. The raw data of time on task was not normally distributed for the total sample and was therefore log transformed to reduce skewness and make it follow a normal distribution more closely. A random effects regression model (Kirkwood & Sterne, 2003) was then used to identify which factors influenced time on task across the four time points. The child was named as the random effect in the model, so that the correlation between the repeated measurements in each child could be taken into account. The children were grouped into the following age groups (AGs); AG-1 (1–7 years old, 4 children), AG-2 (8–9 years old, 3 children), and AG-3 (10–15 years old, 3 children). The independent variables tested for were AG, time point, test number, target number in test, target serial number in time point, and the target's distance to the mouse cursor (short/medium/long). This model adjusts for the varying number of observations between children, such as the number of selected targets or tests. The model also determines if time on task is different for the three distances to mouse cursor. Accuracy was categorized as yes or no (selected or not selected) for each target. In order to analyze accuracy as a function of the independent variables (AG, time point, test number, target number in test, target serial number in time point, and the target's distance to the mouse cursor), a general estimating equation model (GEE) was used (Kirkwood & Sterne, 2003). Similarly to the random effects regression model, the GEE takes into account the repeated measurements made in each child and deals with the varying number of targets and tests completed by each child. The results from the GEE model are presented as the odds ratios (ORs), their 95% confidence intervals (CIs), and the $p$-value. For the statistical analyses, the critical $p$-value was set to $\leq 0.05$.

### Ethics statement

Written informed consent was obtained from all parents on behalf of all children who participated in the study. Parents were made aware that they could withdraw from the study at any time without giving any explanation. Ethical approval for the study was obtained from the Regional Ethical Review Board in Uppsala, Sweden (2010/316).

## Results

Eight children completed the assessment at all four time points while problems with gaze calibration caused missing data in two other children. Overall, a total number of 1,219 targets were presented to the children, of which 868 were correctly selected (71%). The analyses were based on the 868 observations for time on task, and 1,219 observations for accuracy.

Figure 2 shows time on task and accuracy for each child over the time points. Visual inspection of the figure demonstrates that nine children had positive improvements with higher values in accuracy and seven children had positive improvements with lower values in time on task over time. Visual inspection of the Figure 2 also demonstrates a positive outcome for seven children with a pattern of high accuracy and low time on task at the last time point (Emma, Daniel, Max, Adam, David, Marcus, Anna). Jacob, whose performance decreased over time, developed a severe form of treatment-resistant epilepsy during the study. Two children (Isaac and Lucas), who improved in performance over time, ended with lower accuracy at T4 (below 70%) than the other children. These two children had alternating strabismus and struggled to focus and fixate on targets during all the assessments.

### Change in accuracy

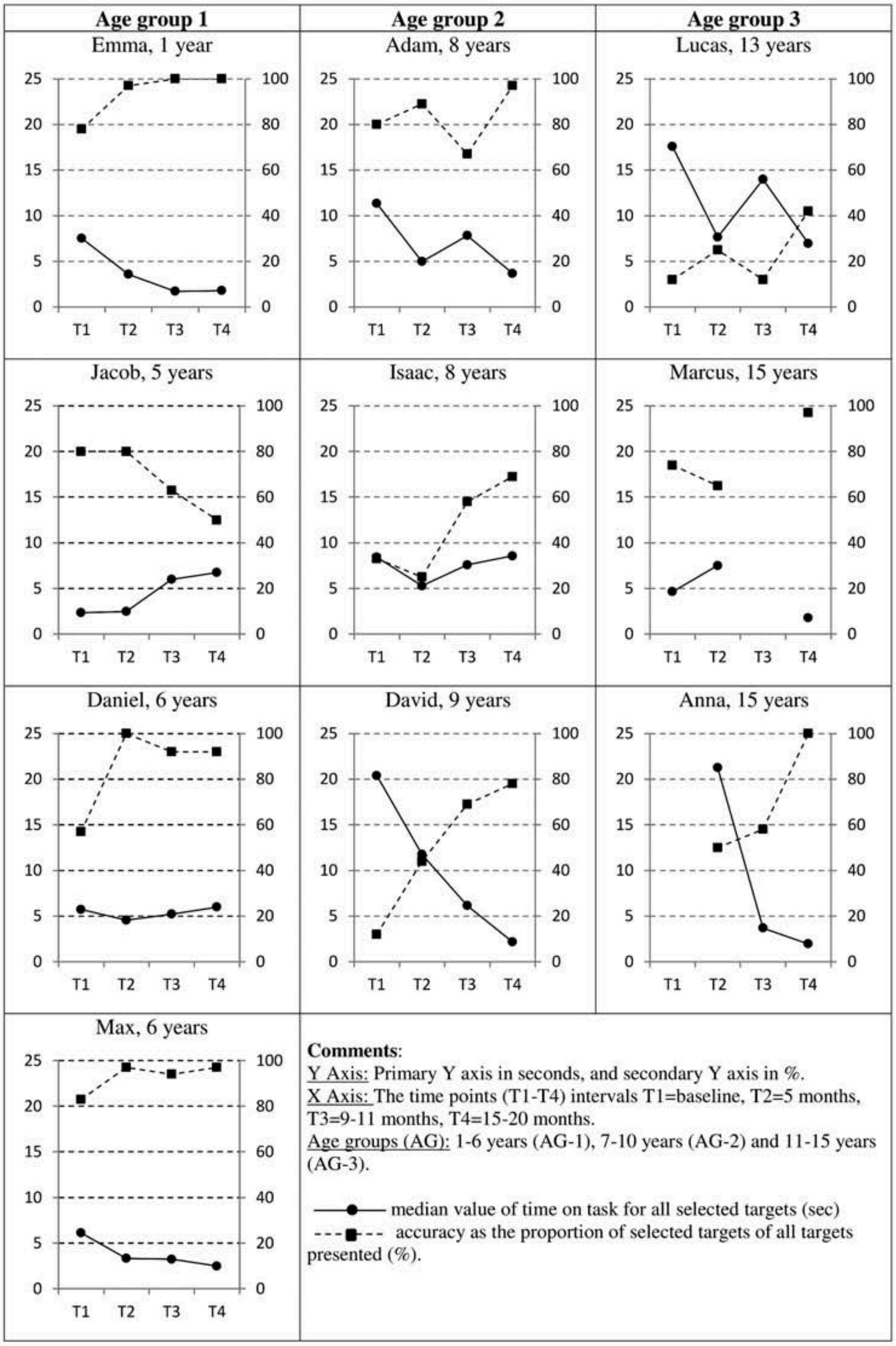
At T4 the children were about three times more likely (OR 3.27, 95% CI = 1.41–7.58, $p < 0.01$) to be accurate (selecting targets) than at T1. While the improvements in accuracy at T2 and T3 were similar (both ORs approximately 1.6), these improvements were not significantly different from T1 ($p = 0.06$, $p = 0.13$, respectively). The GEE also showed that the children became less accurate (OR 0.96, 95% CI = 0.92–0.99, $p = 0.02$) as the target number increased in a test. None of the other variables were found to be independently associated with accuracy. Figure 3 shows children with good to excellent improvements in accuracy, children who improved in accuracy but not so much (children with alternating strabismus), and the child with decreased performance over time (treatment-resistant epilepsy).

### Change in time on task

The results show that children had improved in time on task at T2 compared to baseline. The observations of time on task at each of the time points T2, T3, and at T4 for the whole sample were significantly shorter than time on task at baseline (baseline, median = 6.8 s; T2, median = 4.24 s, $p < 0.01$; T3, median = 3.93 s, $p < 0.01$; T4, median = 3.51 s, $p < 0.001$). The time on task at T4 was also shorter than at T2 ($p < 0.03$). Nevertheless, the maximum and minimum values of time on task did not vary much over the course of the time points (maximum 29.3–30.98 s; minimum 1.01–1.28 s). A weaker association was found between time on task and the AGs. The AG 8–9 years (AG-2) had a significantly longer time on task than the youngest (AG-1) and oldest children (AG-3) ($p = 0.03$) at T1–T3. No such differences were found between AGs at T4. The test number, target serial number in the time point, and distance between the target and the mouse cursor were not associated with time on task.

## Discussion

The findings in this study indicate that these children with severe physical impairments, and who were unable to speak, were able to improve in eye gaze performance over time. The statistical analyses showed that children became faster and more accurate over time in eye gaze performance. Faster performance was recorded as early as 5 months after commencing use of AT. The improvement was stable over the other time points. The analysis showed a trend over time in improved accuracy, which became statistically significant only at the 15–20-month time point. This result shows the persistence of the improvement in accuracy over a long period of time. Thus, as research points out (Donegan, 2012b; Donegan & Oosthuizen, 2006) the result in the present study supports that children with profound impairments may need long period of time to improve in eye gaze performance. However, due to the fact that only 10 children were included, this result needs to be interpreted with caution. The children's



Age group 1

Age group 2

Age group 3

Emma, 1 year

Adam, 8 years

Lucas, 13 years

Jacob, 5 years

Isaac, 8 years

Marcus, 15 years

Daniel, 6 years

David, 9 years

Anna, 15 years

Max, 6 years

**Comments**:

Y Axis: Primary Y axis in seconds, and secondary Y axis in %.

X Axis: The time points (T1-T4) intervals T1=baseline, T2=5 months, T3=9-11 months, T4=15-20 months.

Age groups (AG): 1-6 years (AG-1), 7-10 years (AG-2) and 11-15 years (AG-3).

—●— median value of time on task for all selected targets (sec)

- -■- - accuracy as the proportion of selected targets of all targets presented (%).

**Figure 2.** Time on task (sec) and accuracy (%) for each child at each time point (T1–T4).

poorer eye gaze performance at the beginning of the study is in line with previous research, indicating that it is a challenging task for a user to learn how to use their eyes to control objects on a computer screen (Hansen & Aoki, 2011; Heikkilää & Ovaska, 2012; Skovsgaard et al., 2012). Reduced performance at baseline may be a result of the extra exertion required for a child, inexperienced with gaze-based AT interaction, to fixate steadily on each target and repeat this action several times. In case reports, adult users with severe impairments have reported exhaustion during early stages of learning to use eye gaze-controlled devices (Donegan, 2012b; Najafi et al., 2008). This may be especially true for children with severe impairments. However, the interaction with gaze-based AT supposedly becomes faster and smoother over time as the person learns to use the system for interaction (Heikkilää & Ovaska, 2012), which possibly decreases difficulty over time. Research suggests that familiarization with, and the learning effect from gaze interaction over time may be especially important for gaze-based AT, compared with other input devices, as the novice user has no previous experience of

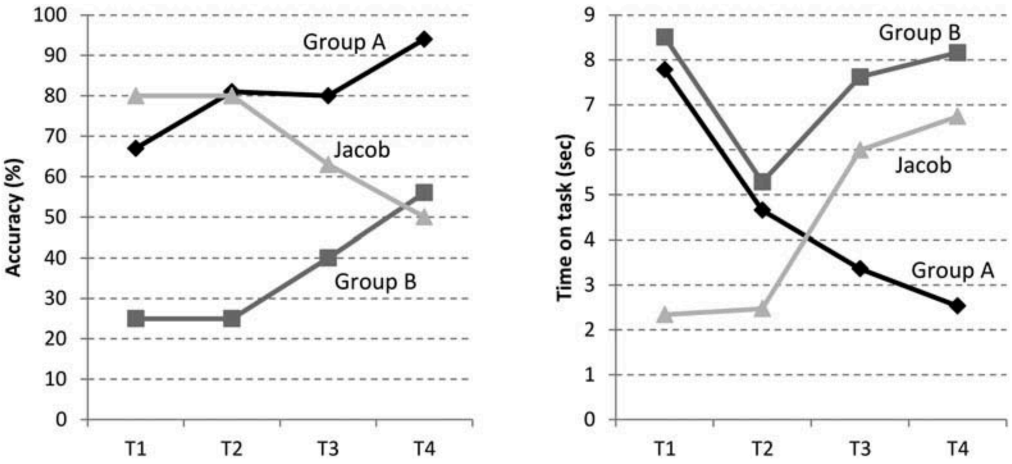


**Figure 3.** Accuracy and time on task (median value) for group A (Emma, Daniel, Max, Adam, David, Marcus, and Anna) gaining functional benefits (accurate and fast), group B (Isaac and Lucas) with not so functional gains (improved accuracy but slow), and Jacob, showing decreased performance over time.

gaze interaction to relate to. There is no natural way to manipulate the outside world with the eyes as the human eye is developed to receive information from the outside (Hansen & Aoki, 2011).

The ages of the children in this sample varied greatly, and the results suggest that age seemed to interfere with the time on task. However, this needs to be interpreted with caution due to the limited number of children in each group (three or four children). That the children in the middle group (8–9 years) should have weaker performance than the younger (1–6 years) and the older children (13–15 years) makes no clear clinical sense. Looking at the children's diagrams (Figure 2), children of all ages seemed to improve in time on task. It is likely that children's accompanying impairments (e.g., strabismus or cognitive impairments) may have confounded the results with the ages. In fact, among these 10 children, the youngest participant had better performance than almost all the other children at all time points. According to the medical records, five children had cognitive impairments. Despite this, nine of the 10 children seemed to improve in eye gaze performance. Pointing at targets with their eye gaze seemed intuitive for the children, which is in line with research suggesting that gaze pointing is an intuitive response method (Majaranta & Donegan, 2012; Stampe & Reingold, 1995). The mouse cursor is placed at the point on the screen that the child looks at, regardless of whether the child intends to select the target, or just looks to explore what happens on the screen. Thus, age may not have any clinically relevant impact on these children's performances, but this needs to be investigated more in future studies. In fact, both children in different ages as well as children with cognitive impairments improved over time in this study.

The children had associated impairments, such as epilepsy and strabismus. Epilepsy is common among children with cerebral palsy, which is important to know as this may have an important impact on learning curve in eye gaze performance in cases where the epilepsy is resistant to treatment. One of the children in this study (Jacob), developed treatment-resistant epilepsy and that probably caused concentration difficulties and tiredness, which seemed to have a negative impact on eye gaze performance. Strabismus is known to be prevalent among children with cerebral palsy (Dufresne, Dagenais, Shevell, & REPACQ Consortium, 2014) and it has been viewed as a potential barrier for using gaze-based AT. Although the present study showed a learning curve with lower efficiency for children with alternating strabismus, this study indicates that even these children can improve in eye gaze performance, which is why they should also have the opportunity to try gaze-based AT.

The rather long intervals between measuring accuracy and time on task were based on the assumption that children with profound and complex impairments need time to learn and master new skills. The results appear to support this assumption as a statistically significant improvement in accuracy was not found until 15–20 months from baseline. A limitation is that there were only three tests at each time point. However, exposing these children to more than three tests, particularly at baseline, seemed impossible as it would have been too challenging for them due to their profound impairments.

A strength of this study is the statistical analyses that accounted for the variation in the number of tests and time points between children. Still, the results of this study need to be interpreted with caution due to the limited number of children included. The change in eye gaze performance may be more variable in a larger group. Doing research on gaze-based AT is challenging as it is still a rather new form of AT. Despite the fact that this study only included 10 participants, it is a total survey as it included all children remitted to one regional pediatric center in Sweden from 2010 to 2013 who requested gaze-based AT. Potential referrals took place in the central areas of Sweden.

Eye movements are related to visual attention and the viewer's interest. Therefore, completing a task during gaze interaction requires the ability to be visually attentive and motivated toward the task over an extended period of time (Mulvey & Heubner, 2011). In addition, performance is strongly connected to the belief in one's ability to master a particular task and persevere until completion, in spite of challenges (Bandura & Locke, 2003). It is possible that the children's interest and motivation to perform the specific task in Compass may have influenced the results. A recommendation is therefore to use parents to rate the children's engagement in the task when measuring eye gaze performance in future studies.

This study deals with how children with profound physical impairments can improve in eye gaze performance over time in a standardized environment. Based on the stages of learning (Parker et al., 2012) and the learning curves found in this study, group A (seven children) became fluent in using eye gaze control skills (over 90% in accuracy and fast performance) while the children with strabismus acquired skills (improved accuracy) but continued to have slow eye gaze performance. The child who developed treatment resistant epilepsy did not acquire new eye gaze control skills. To what extent children in this study generalize the acquired skills and use them in other contexts and situations has not been assessed with Compass in the present study. Using gaze-based AT in the children's real environment, such as the classroom, may be more demanding for the child and may entail more distractions, hence requiring greater effort (Heikkilää & Ovaska, 2012). Further studies in children's real environments are therefore needed. The extent to which the children can make use of their performance capacity during gaze-based AT usage in daily life and fulfill their goals in daily activities, will be investigated in a subsequent study.

### *Clinical implications*

An important clinical implication of this study is that children improved in eye gaze performance over time by training their gaze control skills through regular use of gaze-based AT in daily activities. The practical significance of how children can use the gaze-based AT in daily activities will be reported in a forthcoming study. The findings of this study inform professionals that children with profound impairments have different learning curves due to medical conditions. Children showing poor performance during initial assessments with Compass may need time to practice and use the gaze-based AT over longer periods to improve their eye gaze performance.

The finding that accuracy continued to increase 15 months after commencing the gaze-based AT may be due to the children's profound impairments and that they therefore needed extended time to acquire new skills. For example, case studies and theoretical reasoning suggest that practicing over time with a gaze-based AT may increase eye stamina for some users (Donegan, 2012b), improve weak eye control due to vision problems (Donegan, 2012a), and develop eye control skills (Donegan & Oosthuizen, 2006; Holmqvist & Buchholz, 2012).

Nevertheless, children with difficulties with eye gaze control still need to have access to gaze-based AT. There are no other alternative input devices for most children with severe physical impairments, which is why gaze control may be their only option for performing computer activities. To facilitate eye gaze performance, it is important to enlarge pictures and targets in the children's applications in the gaze-based AT used in daily activities.

Another implication is that children of all ages improved over time, even a child as young as 1 year. A recommendation is therefore that children from the age of 1, as well as children with strabismus, should have the opportunity to try gaze-based AT when needed.

## Conclusions

The results indicate that children with severe physical impairments of all ages can improve in eye gaze performance over time when using gaze-based AT. Children with profound impairments have different learning curves in eye gaze performance, and may need to practice gaze control skills by using gaze-based AT on a long-term basis, in order to become both faster and more accurate in eye gaze performance. Despite different learning curves, most children in this study demonstrated that they acquired eye gaze control skills and thereby provide evidence that children with severe physical impairments can learn to control a computer with their eye gaze.

Building on these results, further studies are needed to investigate the extent to which children with such profound impairments can use gaze-based AT to fulfill their goals in daily activities over time.

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