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Full Length Article

Gaze behaviour during walking in young adults with developmental coordination disorder

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ABSTRACT

Background: Individuals with Developmental Coordination Disorder (DCD) experience difficulty with motor coordination and this affects their daily functioning. Research indicated inferior visuospatial processing and oculomotor control in DCD. As visual information is essential for locomotor control, more insight in the gaze behaviour of this population during walking is required and crucial for gaze training interventions as a possible means to improve daily functioning of children and adults with DCD.

Aim: This study explored differences and similarities in gaze behaviour during walking between typically developing young adults and those with DCD.

Methods and procedures: Ten young adults with DCD (age: 22.13 ± 0.64) and ten typically developing individuals (age: 22.00 ± 1.05) completed a walking task in which they had to place their feet on irregularly placed targets wearing eye tracking glasses.

Outcomes and results: Individuals with DCD walked slower and demonstrated a different gaze strategy compared to their neurotypical peers as they fixated almost each and every target sequentially. Typically developing individuals, on the other hand, directed gaze further along the path and often fixated areas around the targets.

Conclusions and implications: Despite adequate walking performance in daily situations in young adults with DCD, fundamental control deficits persist into adulthood.

What this paper adds?: This paper is the first to demonstrate differences in gaze behaviour between young adults with DCD and typically developing individuals in a task that resembles a task of daily living, as previous research focused on laboratory tasks. This is a valuable finding as DCD has a clear impact on the daily life. Furthermore, this study demonstrated that the fundamental control deficits of DCD persist into adulthood despite frequent performance and practice of these daily tasks. Lastly, these findings might contribute to the therapeutic potential of gaze training interventions to improve the daily functioning of children and adults with DCD.

1. Introduction

Developmental coordination disorder (DCD) is a neurodevelopmental disorder that manifests in impaired acquisition and execution of motor skills in the absence of any demonstrable medical condition. In general, individuals with DCD are those who appear very clumsy. The motor difficulties in DCD present in fine motor skills, like tying shoelaces, and/or in gross motor skills, like walking,

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which makes the disorder very heterogeneous. As also stated in the Diagnostic and Statistical Manual of Mental Disorders Fifth Edition (DSM-5; American Psychiatric Association, 2013), onset of DCD is in early development and the disorder interferes with activities of daily living and academic achievements. Around 5 to 6% of children between 5 and 11 years old are affected by DCD (American Psychiatric Association, 2013), yet it is important to note that the disorder persists into adulthood (Cousins & Smyth, 2003; Kirby, Edwards, & Sugden, 2011). Even though an individual with DCD might have achieved a basic level of expertise in a range of motor skills, movement execution may still appear awkward, slower and more variable than that of peers, or he/she might have developed compensatory strategies.

Previous extensive research indicated problems in the perception and processing of sensory information in DCD. In a meta-analysis of Wilson and McKenzie (1998), impaired visuospatial processing was named the greatest underlying deficiency, as it showed the largest effect sizes. Both in tasks with and without a motor component, individuals with DCD scored lower on visuospatial processing compared to their peers. Another problem related to sensory processing in DCD is the integration of different sources of sensory information (Mon-Williams, Wann, & Pascal, 1999), for example in balance tasks (Bair, Kiemel, Jeka, & Clark, 2012; Deconinck et al., 2008). A particular movement skill in which this problem may become evident is locomotion. Multiple studies indicated inferior walking skills in children (Deconinck, Savelsbergh, De Clercq, & Lenoir, 2010) and adults (Du, Wilmut, & Barnett, 2015) with DCD, mainly when the task was to walk in a challenging environment, like on a treadmill (Deconinck et al., 2006a), when crossing obstacles (Deconinck et al., 2010) and when walking over uneven terrain (Gentle, Barnett, & Wilmut, 2016). An increased variability in gait is seen, which is, as argued by Wilmut, Du, and Barnett (2016) and Gentle et al. (2016), related to a difficulty with the integration of visual and proprioceptive information. Also, while the removal of visual information did not affect the walking pattern of typically developing (TD) children, gait of children with DCD changed significantly as demonstrated by shorter steps and increased medio-lateral sway (Deconinck et al., 2006a). Altogether, these findings indicated inferior visuospatial processing and a decreased ability to re-weight sensory information in individuals with DCD, which still makes them more dependent on vision.

Vision provides information about the environment in which one moves and is therefore key in the coordination of almost all motor actions. The prerequisite is of course that the eyes are directed to the areas that contain the necessary information. This is achieved by a wide variety of functions and eye movement patterns, which appear to be specific to the task (Foulsham, 2015; Land, 2006). For example, during a sequential daily task like tea-making, it was found that each motor action is closely preceded by goal-directed eye movements with approximately half a second (Land & Hayhoe, 2001). This finely tuned temporal coupling facilitates a smooth concatenation of movements. During walking in an uncluttered environment, gaze is directed towards far space, along a future path and to key areas that may reduce uncertainty related to the environment or path (Higuchi, 2013; Jovancevic-Misic & Hayhoe, 2009; Patla & Vickers, 2003). In these situations, visual information, also from peripheral vision, is used in a feedforward manner to anticipate the path (Matthis & Fajen, 2014). However, when walking over uneven terrain or when precise foot placement on certain targets is required, the gaze strategy is adapted and each target is fixated prior to stepping on it (Domínguez-Zamora, Gunn, & Marigold, 2018; Hollands & Marple-Horvat, 2001; Hollands, Marple-Horvat, Henkes, & Rowan, 1995). This change in gaze behaviour is thought to reflect a shift from an anticipatory-based towards an on-line mode of control. In such a cluttered environment, a close temporal linkage between the onset of the eye movement and the start of the leg movement is observed (Hollands & Marple-Horvat, 2001). These findings highlight the importance of a close interaction between the oculomotor and the locomotor system, and hence, the need for proficient oculomotor control in walking.

A number of studies have provided evidence showing that oculomotor control is disrupted in DCD (Katschmarsky, Cairney, Maruff, Wilson, & Currie, 2001; Langaas, Mon-williams, Wann, Pascal, & Thompson, 1998; Robert et al., 2014; Sumner, Hutton, Kuhn, & Hill, 2016). Using a typical antisaccade task, Sumner et al. (2016) showed that children with DCD are less able to supress saccades to salient cues. Furthermore, in a sequential saccade task, fixations of children with DCD are less accurate (Katschmarsky et al., 2001). With respect to smooth pursuit (i.e. a tracking movement of the eye to follow a moving target) children with DCD achieve lower gains and demonstrate more saccadic intrusions than TD children for horizontally moving targets (Langaas et al., 1998; Sumner et al., 2016). Robert et al. (2014), on the other hand, found impairments in vertical pursuit performance, but not in horizontal smooth pursuit. Notably, ocular smooth pursuit is partly reliant on prediction of the future trajectory of the moving target (Kowler, 1990). Therefore, the reduced smooth pursuit performance in individuals with DCD may also reveal the general problem with predictive control (Adams, Lust, Wilson, & Steenbergen, 2014; Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013).

Until now, only a few studies have examined gaze behaviour as a possible contributor to motor problems in non-laboratory based tasks (Licari et al., 2018; Wilson, Miles, Vine, & Vickers, 2013). Wilson, Miles, et al. (2013) found later and shorter tracking of the ball in children with catching difficulties. Licari et al. (2018) found inefficient gaze behaviour in children with DCD during catching characterised by multiple short fixations before ball release and delayed smooth pursuit initiation during flight. Furthermore, interventions that modify gaze strategies of children with DCD seem to improve throwing and catching performance of these children (Miles, Wood, Vine, Vickers, & Wilson, 2015; Słowiński et al., 2019; Wood et al., 2017). Gaze training was found to improve both throwing and catching performance and motor coordination (Słowiński et al., 2019). More specifically, the authors found highly individualised coordination patterns following gaze training, which indicates self-organisation in finding movement solutions. The positive effect of gaze training does not imply that poor ocular control is the (only) factor causing the movement problems of individuals with DCD. The coupling of perception and action is very intricate and other factors such as inefficient feedforward control or inadequate muscle coordination may have imposed atypical gaze patterns too. Yet, these studies highlight that gaze interventions may be a potential tool in facilitating motor learning for DCD. Therefore it is important to investigate whether gaze behaviour is atypical in other daily tasks too (Miles et al., 2015; Słowiński et al., 2019; Wood et al., 2017).

Since visual information is crucial during locomotor tasks, more insight in the gaze behaviour of individuals with DCD during walking is required and this might possibly contribute to the therapeutic potential of gaze training interventions in this population.

Therefore, the aim of the current descriptive study is to explore differences and similarities in gaze behaviour during walking. This study will focus on young adults as this group is often overlooked in DCD research, despite the persistent difficulties that they encounter in daily life.

2. Methods

2.1. Participants

Twenty individuals, aged 20 to 23, of which 10 met the criteria for DCD, participated in this study. The participants with DCD (age: 21.90 ± 0.88) were recruited from a pool of participants that were involved in previous studies (Deconinck et al., 2006a; Deconinck et al., 2006b). They all had received a formal diagnosis by a paediatrician after clinical, including a neurological and motor coordination assessment, and psychological examination during childhood and this served as the inclusion criterion for this group. At the time of the diagnosis no comorbid disorders were present. To verify the motor problems at the time of the present study, they were all re-assessed with the Movement Assessment Battery for Children 2 (MABC-2) (age band 3; Henderson, Sugden, & Barnett, 2010). This test is designed and norm-referenced up to the age of 16, however, it appeared feasible for motor assessment in young adults, aged 15 to 21 years old, with Asperger syndrome (Borremans, Rintala, & McCubbin, 2009). Moreover, previous research in young adults with DCD indicated that the MABC-2 was able to discriminate between poor and typical competence (Baldauf & Deubel, 2010; Du et al., 2015; Wilmut, Byrne, & Barnett, 2013). The individuals with DCD included in the present study scored in the 16th percentile or below. The control group (age: 22.00 ± 1.05) consisted of TD individuals who were students at Ghent University. These participants were matched pairwise to the participants of the DCD group based on birth year and gender. They had never been diagnosed with a developmental disorder or medical conditions that could affect motor behaviour or involve mental retardation and scored above the16th percentile on the MABC-2. All participants had normal or corrected-to-normal vision and gave informed consent prior to the start of the study. The study was approved by the local Ethics Committee of the Ghent University Hospital and conducted in accordance with the Declaration of Helsinki. See Table 1 of the supplementary data for an overview of the participants' characteristics.

2.2. Materials

Eye movements were recorded with the SensoMotoric Instruments (SMI) (SensoMotoric Instruments, 2016) Eye Tracking Glasses 2 Wireless (ETG). These mobile eye tracking glasses were connected to a smart recorder running the iViewETG software, which was worn in a waist bag. Infrared lamps are built into the frame of the glasses and used to illuminate the eye. Through an infrared camera, the position of the pupil of the eye and hence the direction of gaze, could be determined. The ETG have a binocular sampling rate of 60 Hz. The gaze tracking accuracy of the device is 0.5° and the gaze tracking range is 80° horizontally and 60° vertically. A scene camera, built into the frame of the glasses, records the forward view of the participant with a resolution of 960 × 720 pixel at 30 Hz with a field of view of 60° horizontal and 46° vertical. The walking movement of the participant was recorded with a digital camera with a sampling rate of 30 Hz (Casio 100 EXF1, Tokyo, Japan). The camera was placed in the corner of the room filming the complete walking path of the participant. To synchronize the recordings of the scene camera of the ETG and those of the digital camera a synchronisation signal was given with a clapperboard before onset of the trial.

2.3. Procedure

The protocol involved a stepping task similar to the stepping stone task used in Hollands and Marple-Horvat (2001). Participants performed the task with the calibrated (five-point calibration) eye tracking system mounted on the head. The eye tracking glasses were securely tightened to the head of the participant with an adjustable sports strap. During the calibration prior to the experiment it was ascertained that the glasses did not restrict the gaze behaviour of the participants and that the pupil of the eye could be captured

Table 1
Characteristics (mean ± SD) of the included participants.

	DCD	TD
Gender (number of participants)	7 male 1 female	7 male 3 female
Age (year)	22.13 ± 0.64	22.00 ± 1.05
Body height (cm)	181.88 ± 7.15	181.30 ± 8.35
Body weight (kg)	79.30 ± 15.27	71.50 ± 10.68
M-ABC percentile	9.33 ± 7.35	71.60 ± 12.07
Dominant hand (number of participants)	4 left 4 right	1 left 9 right
Glasses (number of participants)	3	0
Lenses (number of participants)	1	5
Tracking ratio (%)	97.71 ± 1.34	97.78 ± 1.03
Fixation ratio (%)	69.44 ± 0.06	73.27 ± 0.04

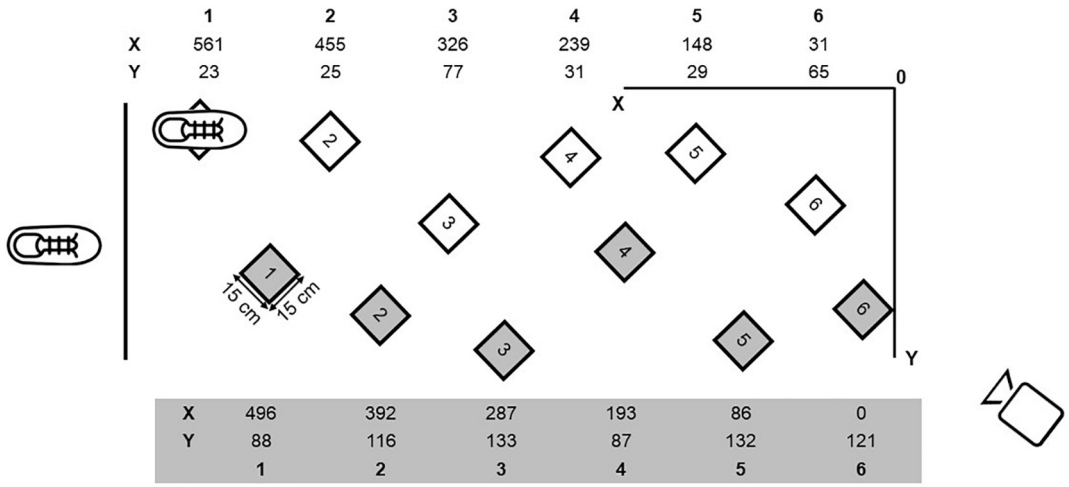

Fig. 1. Top view of the lay-out of the path. The stepping stones were squares of 15 cm by 15 cm, which were laid out in a similar manner, requiring deviations to the left and the right. The x-y position of each stepping stone was adjusted to the participant's body height by multiplying body height with the dimensionless x and y-values. Example x-y positions are given for the left (top table) and right (bottom table) for a participant with a body height of 187 cm. A camera was placed in the corner of the room filming the complete sequence.

for the required field of view, both when looking forward and when looking down. They were instructed to walk at their own preferred pace on a sequence of 12 irregularly placed stepping "stones", i.e. a 15x15cm square sheet of plastic, also referred to as "targets", (for details, see Fig. 1). The pattern was scaled to body length, so that each participant was equally challenged. To clearly indicate the path, the stones for the left foot were yellow, those for the right foot were green. Before each trial, the participants were standing behind a starting line with their left foot on the first stepping stone and waited until a starting signal was given. The task was first demonstrated, followed by a practice trial. Ten trials were recorded.

2.4. Data analysis

2.4.1. Inclusion criteria

Eye movements were analysed using the standard settings and algorithms in BeGaze 3.7 (SensoMotoric Instruments, 2014). Trials with disproportionate loss of data were excluded from the study. Consistent with previous research (Vansteenkiste et al., 2017) the cut-off values used in this procedure were: 1) tracking ratio (i.e. the percentage of time that eye movements were effectively measured) smaller than 85%, 2) fixation ratio per participant smaller than 60% of the total duration of the trial. This procedure showed unreliable recordings in two individuals with DCD. So, in total, data of 18 participants was used for further analysis. The remaining gaze data indicated a lower fixation ratio in the DCD group. However, no significant differences were found between the groups for tracking ratio ($t(16) = 0.12$, $p = .905$) and fixation ratio ($t(16) = 1.62$, $p = .125$). See Table 1 for the characteristics of these participants.

2.4.2. Locomotor behaviour

The recordings of the walking movement were processed using Kinovea (open source video analysis software). This involved manual determination of the start and end of a trial, defined as the first movement of the right foot (i.e. the last frame in which the toes still touch the ground) and the moment of the last foot placement (i.e. the frame in which the foot fully touches the ground). The *swing phase* of each foot movement was determined as the time between the first frame in which the toes leave the ground and the frame in which the foot fully touches the ground. The *stance phase* was defined as the time between the end of the swing and the beginning of the next swing movement. The duration of each sub-movement and the *total movement time* was calculated accordingly.

2.4.3. Eye movements

In BeGaze 3.7, fixations, blinks and saccades were determined through the SMI fixation detection algorithm (of which details are not revealed by SMI). Using the "Semantic Gaze Mapping protocol", all fixations were assigned to one of the Areas Of Interest (AOIs), i.e. the targets (represented by L for left or R for right and the sequence number), F1, F2 and F3+ for when the gaze was directed on the area around or in between stepping stones, respectively one, two and three or more stepping stones in front of the one the participant was standing on. Then the extent to which gaze was directed to the targets during the trial was calculated as the number of targets fixated out of 12, expressed as a percentage. In order to explore the proactive behaviour of the individuals, we determined the *number of fixations ahead by categorising* each fixation as 0, 1, 2, 3 or more steps ahead of the current step. To this end, the interval between the previous foot placement (or the start of the trial for the first step) and the current foot placement was defined as the current step and gaze location (i.e. the start of a fixation on a target AOI) was determined relative to this step. In case that multiple fixations occurred during this interval, each fixation was counted separately. Based on the start and end times of the fixations, the

following other dependent variables for gaze behaviour were computed per trial and per AOI. First, the *total number of fixations* and the *number of fixations per second,* i.e. the number of fixations divided by the total fixation time of one trial, were considered. The *average fixation time*, i.e. the average duration of one fixation, was considered and the *total fixation time* was computed as the sum of the duration of all fixations. *Relative fixation time* was the total fixation time on an AOI divided by the total fixation duration of a trial.

2.5. Statistics

For each individual the mean (M) and standard deviation (SD) of all dependent variables across trials were calculated. Seven separate MANOVAs, i.e. one for each family of variables (gait timing, number of fixations, number of fixations per second, number of fixations ahead, average fixation time, total fixation time and relative fixation time) were conducted using SPSS Statistics 26 to evaluate differences between the DCD and the control group. Both multivariate and univariate effects were examined. Independent samples *t*-tests were run for variables with missing data as MANOVA excludes out these cases listwise by default in SPSS. This was the case for the average fixation time. To reduce the risk of making Type 1 Errors, two stages of corrections were applied. First, the alpha level of 0.05 was divided by the total number of groups of variables tested in a MANOVA or t-test (i.e. 7), resulting in an adjusted alpha level of 0.007. Then, the Benjamini & Hochberg correction was applied to the initially adjusted alpha level to control the false discovery rate (for an overview see Cramer et al., 2016; Benjamini, Drai, Elmer, Kafkafi, & Golani, 2001). All multivariate and univariate effects are reported relative to the adjusted alpha levels. Effect sizes were calculated as partial eta squared (partial η^2), for the MANOVAs, and Cohen's d (d), for the t-tests. The same analyses were used for the supplementary data.

3. Results

All participants were able to execute the walking task as instructed, they all placed their feet on the indicated stepping stones. However, individuals with DCD took approximately 25% more time to complete the total walking sequence. In addition, all sub-movements appeared to be slower in this group. Statistical significance was reached for total movement time and the swing phase of the gait cycle (Table 2).

Qualitative evaluation of the gaze data revealed clear differences in the gaze behaviour of individuals with DCD compared to the TD group. Video illustrations of the gaze sequences of each group can be found in the supplementary material (Video link). A representative trial for each group is given in Fig. 2. The first stepping stone, on which the foot was placed before the start of the trial, was rarely fixated by any of the participants. Furthermore, we observed that six individuals with DCD fixate almost every stepping stone sequentially along the walking path, whereas none of the TD individuals demonstrated this gaze behaviour strategy. TD individuals often "skip" the first targets and direct their gaze further along the path. Besides, TD individuals often fixate the area around the targets instead of the targets, as indicated by fixations on F1, F2 and F3+. Table 3 gives an overview of the percentage of trials in which all or only a certain number of stepping stones are fixated. In around 65% of the trials, individuals with DCD fixate 9 or more of 12 stepping stones. This was only the case in around 4% of the trials of the TD group.

Quantification of how far ahead the participants directed their gaze confirmed the qualitative findings. Individuals with DCD made significantly more steps with their gaze directed to one or two targets ahead compared to the control group (Table 4).

Detailed analysis of gaze behaviour demonstrated significant differences in the total number of fixations per trial between the groups. Individuals with DCD had significantly more fixations on the target (16.18 ± 4.89) than the TD group (8.24 ± 2.10); ($F(1,16) = 21.71$, $p < .001$, partial $\eta^2 = 0.576$). Inspection of the number of fixations per target showed more fixations in individuals with DCD compared with the TD individuals for targets L2, R2, R3, L4 and R5. See Table 2 of the supplementary data for details per AOI. Also for the number of fixations per second, significant differences were found between the groups. Individuals with DCD had significantly more fixations per second on the target (2.64 ± 0.73) than the TD group (1.57 ± 0.53); ($F(1,16) = 13.16$, $p = .002$, partial $\eta^2 = 0.451$). For the individual targets, higher numbers of fixations per second were found in the DCD group for targets R2, R3, L4 and R5. See Table 3 of the supplementary data for details per AOI on this variable.

Average duration of fixations on the first ten targets, except for target 8 (R4), were longer in the DCD group compared to the TD group (see Table 4 of the supplementary data for an overview). Fixations on the last two stepping stones and on F1 and F3+ were longer in the TD group. Average fixation duration on L6 was significantly longer in the control group (336.09 ± 64.84) compared to the DCD group (235.14 ± 52.60) ($t(16) = 3.56$, $p = .003$, $d = -1.557$).

Finally, significant differences were apparent for the fixation times per AOI (multivariate effect: $F(4,13) = 5.73$, $\Lambda = 0.362$, $p = .007$, partial $\eta^2 = 0.638$). Individuals with DCD spent in total almost twice as much time fixating the stepping stones than TD

Table 2
Gait timing variables (mean ± SD) (in ms) of individuals with DCD and TD and the results of the MANOVA.

	DCD	TD	F(1,16)	p	Partial η^2
Multivariate effect			4.52	0.020	0.492
Swing	613.94 ± 59.86	518.03 ± 46.80	14.60	0.002*	0.290
Stance	803.84 ± 328.60	588.61 ± 97.61	3.91	0.065	0.477
Total movement time	8432.63 ± 2023.30	6696.81 ± 685.15	6.52	0.021	0.197

* Significance.

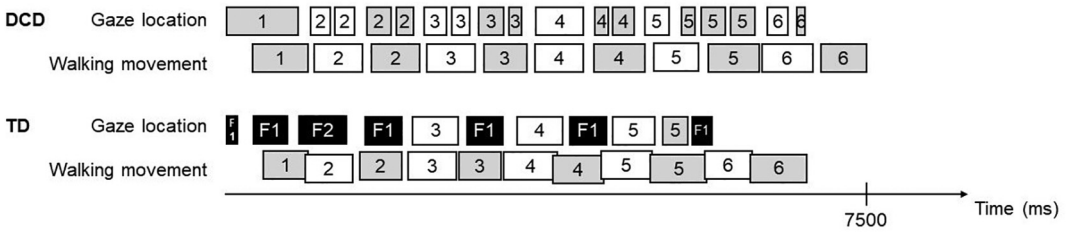

Fig. 2. Representative time courses of gaze location and walking movement for each group. For walking movement, the bars represent the swing phases. Grey indicates fixation on or swing towards a target on the right, white a target on the left. Black bars indicate fixations around the targets, one (F1), two (F2) or three or more (F3+) stepping stones ahead.

Table 3
Percentage of trials in which all or only a specific number of stepping stones were fixated (in %) for each group.

	DCD	TD
All	1.33	0
11	25.33	1.02
10	22.66	0
9	16	3.06
8	8	7.14
7	9.33	13.27
6	6.67	11.22
5	2.67	17.35
4	5.33	18.37
3	2.67	19.39
2	0	8.16
1	0	1.02

Table 4
Number of fixations (mean ± SD) per trial directed 0, 1, 2, 3 or more than 3 targets ahead relative to the one they were standing on for each group and the results of the MANOVA.

	DCD	TD	F(1,16)	p	Partial η^2
Multivariate effect			9.48	0.001*	0.798
0	0.49 ± 0.75	0.02 ± 0.06	4.02	0.062	0.201
1	9.23 ± 5.67	1.60 ± 1.61	16.69	0.001*	0.511
2	4.49 ± 2.11	1.07 ± 0.81	22.43	< 0.001*	0.584
3	1.21 ± 1.16	1.87 ± 1.18	1.41	0.253	0.081
More	0.47 ± 0.79	3.68 ± 2.12	16.41	0.001*	0.506

* Significance.

individuals ($F(1,16) = 16.01$, $p = .001$, partial $\eta^2 = 0.500$)(Fig. 3). On the other hand, the control group directed gaze twice as long towards an area around the stepping stones three or more steps ahead ($F(1,16) = 10.06$, $p = .006$, partial $\eta^2 = 0.386$). However, this effect was not significant after the alpha level adjustment. For relative fixation time significant differences were found for the time on the targets ($F(1,16) = 16.76$, $p < .001$, partial $\eta^2 = 0.512$) and the time on areas around the stepping stones three or more steps ahead ($F(1,16) = 21.92$, $p < .001$, partial $\eta^2 = 0.578$), the former being longer in DCD and the latter being longer in TD individuals (Fig. 3).

4. Discussion

The purpose of this study was to gain insight into the gaze behaviour of young adults with DCD during walking. It was found that the individuals with DCD used a very different gaze strategy when negotiating a path determined by stepping stones. More in particular, their eyes fixated (almost) each and every stepping stone sequentially, along with the steps. This meant that gaze of the individuals with DCD was directed to the stepping stone to which a step was made and shifted to the following stepping stone prior to or while making that step towards it. TD individuals, on the contrary, directed their gaze further on the path and had more fixations on areas around the stepping stones.

In line with the general movement profile of DCD, participants with DCD walked slower compared to the control group. The instruction was to walk at a self-selected pace that was comfortable for the participant itself and to place their feet on the stepping stones, which all participants did correctly. By requiring participants to place their feet on predetermined targets, the balance

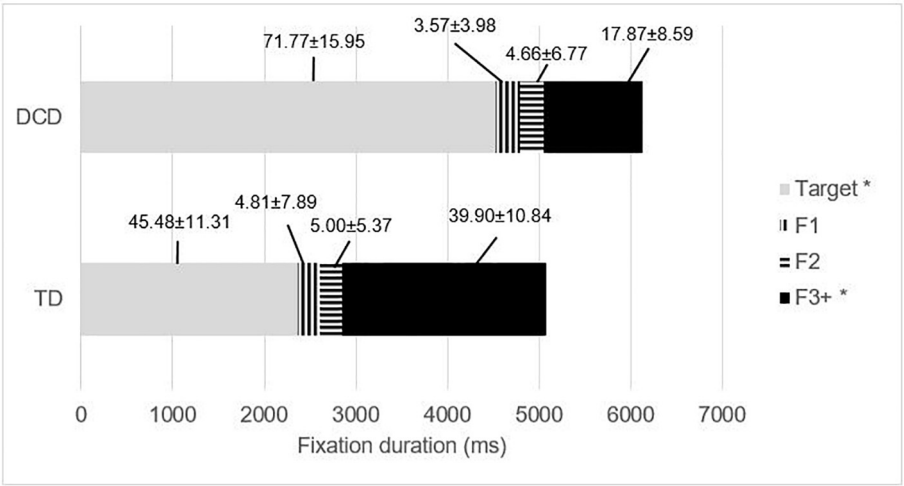

Fig. 3. The total duration of the fixation time (i.e. sum of duration of all separate fixations) on each of the stepping stones, indicated as target, F1, F2 and F3+ per trial. The numbers on the figure indicate the relative fixation time. *Significance.

demands were higher in this task compared to normal walking. This seemed to affect the DCD group more than the neurotypical participants, leading to a slower and therefore safer walking pattern in this group, which is in accordance with previously reported balance problems (Deconinck et al., 2010) and slower walking patterns when walking over cluttered terrain (Cousins & Smyth, 2003).

Importantly, next to a safer walking strategy, we observed different gaze behaviour in the DCD group compared to the neurotypical young adults. No instructions on where to look were given, so gaze was allocated completely voluntarily. Individuals with DCD opted to foveate the stepping stones for a larger amount of time compared to the control group and the average fixation duration on these targets tended to be longer in this group. Hence, it seems that young adults with DCD need more time to extract the relevant information from the targets on which they had to place their feet. Besides, it is known that gaze is generally allocated to areas of interest to reduce uncertainty related to the spatial coordinates of stepping stones or obstacles and other environmental characteristics (Jovancevic-Misic & Hayhoe, 2009). In that respect, individuals with DCD appear to have a higher need to establish certainty about the location of the targets compared to TD individuals. This "locking of gaze" to nearby locations suggests an increased reliance on visual information for guiding and controlling actions and is consistent with previous work. For example, Gentle et al. (2016) found that individuals with DCD inclined their head more towards the ground during walking on irregular terrain. Another study reported that walking is affected by the removal of visual information in children with DCD (Deconinck et al., 2006a). Similar effects were observed in balance tasks (Cousins & Smyth, 2003; Deconinck et al., 2008; Wann, Mon-Williams, & Rushton, 1998) and manual aiming tasks (Biancotto, Skabar, Bulgheroni, Carrozzi, & Zoia, 2011; Smits-Engelsman, Wilson, Westenberg, & Duysens, 2003; Van Waelvelde et al., 2006). This increased reliance on vision is suggested to be due to a decreased ability to re-weight the different sources of sensory information (e.g. in balance) and/or a reduced ability to generate forward estimates of movement. The gaze pattern found in the current experiment may be a reflection of these deficiencies during gait, however, future studies focusing on the underlying control mechanisms are needed to clarify this. Overall, individuals with DCD seem to be more affected by the removal of vision during movement and seem to rely on an increased visual sampling of the targets in the current task. It should be noted that in this task, information from peripheral vision could still be attended using covert attention, yet, this could not be captured using the eye-tracker in this experiment.

TD individuals, on the other hand, do not consistently require foveation on the targets as they foveated areas around the targets. This is in accordance with the general findings in walking over cluttered terrain in neurotypical individuals (Matthis & Fajen, 2014; Patla & Vickers, 2003). Similar behaviour, wherein longer fixations on positions that do not directly provide relevant information were used, was found in sports contexts (Vater, Williams, & Hossner, 2019). This behaviour reduces the cost of executing saccades and may suggest that the TD individuals covertly monitor the location of the targets in the periphery. Alternatively, this group may use previously recorded spatial information stored in short-term memory. Neurotypical individuals are relatively good at using this type of information, yet in children with DCD this appeared to be problematic, which may lead them to adopt the gaze strategy observed in this task (Biancotto et al., 2011). Taken together, individuals with DCD rely on foveal information of the stepping stones, whereas TD individuals do not require foveation of the targets and may use alternative sources to guide the walking movement.

Next to a smaller need to foveate the stepping targets, it was found that gaze of TD individuals was directed further along the path. Hence, they acquire the visual information of the targets more in advance and are able to anticipate the upcoming path (Higuchi, 2013). This allows for feedforward control and adjustments to accurately negotiate the walking trajectory and is the standard mode of control in neurotypical adults (Patla & Vickers, 2003). In contrast to their TD peers, individuals with DCD did not direct their gaze far ahead, which may suggest a mode of control that puts greater emphasis on on-line visual information. This feedback-based strategy during walking is also observed in older adults, especially those at higher risk of falling (Yamada et al., 2012). While this strategy may be a necessary adaptation to cope with individual demands (e.g. related to balance), research in neurotypical individuals has shown

that when vision is constrained to less than two steps ahead, walking performance is slower and less accurate (Matthis & Fajen, 2014). In other words, an experimentally imposed, inefficient gaze that matches the strategy observed in our DCD group slows walking speed in neurotypical adults, which is in line with the observations in the individuals with DCD. Individuals with DCD are known to have a reduced ability to use predictive control, which may force them to use slower sensorimotor feedback (Adams et al., 2014). Yet, based on the current experiment it is impossible to determine the actual cause of this atypical control strategy and whether this induces a lower walking speed. Vice versa, this lower walking speed in individuals with DCD may impose a different gaze pattern. In TD individuals, the visual buffer, which is the time span between what they visually perceive and their motor actions (Land, 2006; Vansteenkiste, 2015), that allows for on-line control is around 2 s. This implies that the area that is relevant for the on-line guidance of locomotion stretches further ahead when moving faster (Vansteenkiste, 2015). Consequently, TD individuals look further ahead compared to individuals with DCD, whose lower walking speed directs their gaze towards the more direct environment. Whether the locomotor difficulties in DCD constrain their gaze strategy or whether their gaze strategy impacts their walking performance or a combination of both directions is yet to be investigated. Furthermore, prior to implementing strategies that intend to change the gaze strategy, it is warranted to unravel the causes for the atypical behaviour in individuals with DCD.

Next to differences in the spatial allocation of gaze, we measured an increased number of fixations in the DCD group on the targets. These differences when persisted controlling for the trial duration, so individuals with DCD executed more repeated fixations per second. This might indicate that individuals with DCD executed (micro-)saccades when fixating a certain target. In this respect it is worth noting the slightly smaller, albeit not significant fixation ratio in the DCD group compared to the TD group. Unfortunately, the equipment used (BeGaze 3.7, SMI, Teltow, Germany) does not allow us to examine the nature of the eye movements more closely, however, the higher number of saccades in individuals with DCD is in line with previous findings from a sustained fixation task (Sumner et al., 2016) and might indicate less stable gaze. Unstable gaze might complicate the acquisition of valuable information from the environment to coordinate locomotion and may suggest a fundamental oculomotor control problem (Crowdy, Hollands, Ferguson, & Marple-Horvat, 2000; Sumner et al., 2016). It is known that the cerebellum plays a crucial role in the coordination of oculomotor and locomotor control (Marple-Horvat, Criado, & Armstrong, 1998; Stein, 1986). Also, the unsteady gait of patients with cerebellar ataxia has been partly related to their impaired oculomotor control (Crowdy et al., 2000). In this respect, it is interesting to note that neuroimaging studies and research into temporal control have suggested involvement of cerebellar areas in children with DCD too (Brown-Lum & Zwicker, 2015; Ivry, 2003; Lundy-ekman, Ivry, Keele, & Woollacott, 1991). However, the differences in oculomotor control may also be a consequence of a more generalized problem with balance in the individuals with DCD and more research is required to reveal the underlying mechanism of these findings.

This study is the first to investigate and describe gaze behaviour in young adults with DCD during a locomotor task. Although locomotion comprises an important part of the daily functioning and locomotive skills already start developing in early childhood, certain differences in the control of walking are apparent in young adults with DCD compared to TD young adults. This indicates that, despite adequate walking performance (Cousins & Smyth, 2003; Du et al., 2015), fundamental differences in control persist into adulthood in DCD. While our findings applied to all individuals with DCD of our sample, we do acknowledge that the sample size is relatively small. Given the known heterogeneity of the population with DCD, our results should by generalized with caution. We are confident that all participants complied with a DCD diagnosis in adult life. In the absence of a motor test battery that assesses motor difficulties in adults, the MABC-2, which is norm-referenced up to the age of 16, was used to confirm the diagnosis. Despite this limitation, the battery was able to distinguish between low and high motor competence in our sample. Besides, the degree to which the motor difficulties interfere with activities of daily living at this older age (criterion B of the DCD diagnosis) was not formally assessed in our sample. Furthermore, the aim of this study was to explore gaze behaviour in a task that resembled daily life. Therefore we opted for an ecologically-valid task with few experimental restrictions. Although this led to reliable and interesting results, the inevitable limitation is that our protocol does not allow us to draw any conclusions regarding underlying mechanisms of the interaction between oculomotor and locomotor control in DCD.

Nevertheless, the current findings demonstrate clear differences between the gaze behaviour of individuals with DCD and that of their TD peers during walking. These are valuable findings as walking is essential in daily life and DCD has an impact on daily functioning. The gaze strategy we observed in young adults with DCD seems to reflect unstable oculomotor control and an increased dependency on on-line foveal visual feedback of the walking path. Yet, future research should investigate which of and the extent by which these suggested underlying control problems contribute to the walking difficulties and overall daily functioning in DCD. Furthermore, the potential of gaze training interventions during walking may be considered, given the promising findings in catching and throwing in DCD (Miles et al., 2015; Wood et al., 2017) and in walking in cerebellar patients (Crowdy et al., 2002).

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