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Multisensory Integration in Children with Developmental Coordination Disorder

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Abstract

This study examines how multisensory stimuli affect the performance of children with Developmental Coordination Disorder (DCD) on a choice reaction time (CRT) task. Ten children with DCD, identified using the Movement Assessment Battery for Children-2, aged 7-10 years (4F, M=8y3m, SD = 17m) and 10 typically developing peers (TDC) (5F, M=8y4m, SD = 17m) reached to unimodal (Auditory (AO), Visual (VO)) and bimodal (Audiovisual (AV)) stimuli at one of three target locations. A multisensory (AV) stimulus reduced RTs for both groups [$p < 0.001$, $\eta^2 = 0.36$]. While the children with DCD had a longer RT in all conditions, the AV stimulus produced RTs in children with DCD (494ms) that were equivalent to those produced by the TDC to the VO stimulus (493ms). Movement Time (DCD=486ms; TDC=434ms) and Path Length (DCD = 25.6cm; TDC = 24.2cm) were longer in children with DCD compared to TDC as expected ($p<0.05$). Only the TDC benefited from the AV information for movement control, as deceleration time of the dominant hand was seen to decrease when moving to an AV stimulus ($p<0.05$). Overall, data shows children with DCD do benefit from a bimodal stimulus to plan their movement, but do not for movement control. Further research is required to understand if this is a result of impaired multisensory integration.

Keywords: DCD, Multisensory Information, Kinematics, Aiming

Highlights

- Children with and without DCD react quicker to a bimodal stimulus
- TDC need less time to decelerate to the target when it emits sound.
- Multisensory integration for movement control is impaired in children with DCD

1. Introduction

Developmental Coordination Disorder (DCD) is a neurodevelopmental disorder that is characterised by poor fine and/or gross motor coordination (APA, 2013). Depending on how the APA assessment criteria are interpreted and applied, prevalence in the UK is estimated at between 1.7-6% of primary school aged children (Lingham et al., 2009). Due to its high prevalence there is now a vast body of literature that has tried to understand the mechanisms of DCD in an attempt to optimise therapy.

Goal orientated upper limb tasks have been extensively studied as a window into movement deficits of children with DCD (Wilmut, Wann and Brown, 2006; Biancotto et al., 2011; Astill, 2007) with the planning and execution of these tasks often measured using reaction time (RT) and movement time (MT) respectively. Research shows that children with DCD exhibit slower, more variable RTs than typically developing children (TDC) as a result of either slower processing speed, inefficient preparation of movement or both (Henderson, Rose and Henderson, 1992; Hyde and Wilson, 2011; Debrabant et al., 2013). Similarly, MTs are frequently reported as longer in children with DCD compared to TDC (Astill, 2007; Hyde and Wilson, 2011; Biancotto et al., 2011) perhaps as a result of a heavier reliance on visual information for movement control (Adams et al., 2014).

The planning and execution of hand movements require information about the position of the hand and the location of the target, so that it can be transformed into signals activating the appropriate muscles in order for the hand to reach the respective target. This sensorimotor transformation represents the internal representation of the relationship between visual space and motor space, or the internal model (Wolpert & Ghahramani, 2000). Recently, it has been suggested that the currently available data point to children with DCD having an internal modelling deficit which can be behaviourally manifested in, for example, more variable and slower MTs (Wilson et al., 2013). Information about target location is critical to producing a viable forward model of action, and can be provided by multiple sensory modalities, as multisensory information. These sensory stimuli can provide information about where the object or target is and planning the action to intercept/interact with the target, and the object or target qualities themselves (Jeannerod, 2006).

There is a large body of research which suggests that children with DCD display visual processing deficits (van Waelvelde, de Weerdt, de Cock, & Smits-Engelsman, 2004; Wilson & McKenzie, 1998: Tsai et al., 2008) and this directly impacts on a child with DCD in terms of being able to plan and execute simple aiming and reach to grasp actions (Biancotto et al., 2011). Multisensory integration has been implicated as a deficit in children with DCD, with past research shows that children with DCD have difficulty with cross modal transfer of information (Sigmundsson, Ingvaldsen and Whiting, 1997) and the integration of information from multiple senses (Bair, Kiemel, Jeka and Clark, 2012). More specifically, Bair et al., (2012) suggest that children with DCD weighted information from touch (haptic) and visual information differently while attempting to maintain a steady posture, and concluded that in children with DCD, multisensory integration or fusion is impaired, and this contributes to their general motor deficit.

While the Bair et al., (2012) study considered the fusion of touch and visual information there is no one study that has examined if children with DCD can fuse auditory and visual information and then make use of the multisensory enhancement that an audiovisual stimulus provides to aid planning and execution movement. In general, when visual and auditory stimuli are presented in close spatial and temporal correspondence they become 'bound' into a single perceptual entity, the result of which is an enhancement of the neural response to the stimuli (see Stein and Stanford, 2008 for a review). In healthy adults

Hecht et al., (2008) have shown that combinations of multisensory signals e.g. audio and visual stimuli (bi-modal) could be detected faster (i.e. a shorter RT) than either of these signals presented separately (unimodal). A similar set of data are revealed when considering saccadic eye movements in that when saccades were made to visual and auditory targets their reaction times were decreased, and accuracy increased compared to those generated to unimodal stimuli (Frens., Van Opstal, & Van der Willigen, 1995; Bell, Meredith, van Opstal, Munoz, 2005). In children, postnatal development plays an important role in the maturation of multisensory facilitation. For example, Brandwein et al., (2011) showed that multisensory facilitation of behaviour (i.e. quicker RTs to an audiovisual task) is present in (typically developing) children as young 7, but adult levels are not reached until about 14 years of age.

While it has been shown that audiovisual stimulus can drive shifts in attention to the target resulting in a decrease in RT, if the stimulus is seen as relevant to a movement goal it can also mediate the processes involved in movement execution (Talsma, Doty, Woldorff, 2007). Evidence in humans and non-human primates suggests that other sensory information is integrated with auditory information in the auditory dorsal pathway, and taken together, research shows that motor and auditory information, once coupled, can be reciprocally activated by inputs to either end of the dorsal pathway (Warren, Wise and Warren, 2005). Indeed, research shows that the advantages of multisensory information extend beyond planning to movement execution. For example, in adults a bimodal stimulus produced a more forceful response than a unimodal stimulus (Giray & Ulrich, 1993). This potential bi-sensory coactivation within the motor system was also supported by Plat et al., (2001) who showed that while the modulation of force amplitude was not affected by bimodal stimulation, the time needed for the force signal to reach its maximum amplitude was shorter with a bimodal signal compared to a unisensory one. While Utley, Nasr and Astill (2011) have previously shown that a ball (visual stimuli) that emitted broadband sound (audio stimuli) was more successful in aiding development of catching and throwing skills over a 4 week training period, research that has examined if combinations of stimuli aid movement control during execution, even in typically developing children is limited. It could be that multisensory information might support children with and without DCD in the generation or updating of internal models for executing upper limb movements, and this may be reflected in the movement kinematics of the limbs.

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In light of the above, here we investigate the performance of children with DCD and age matched controls on a multisensory aiming task. The aim of this study was to examine whether multisensory enhancement asserts its effect on the perceptual/planning part of the movement (RT) or the execution of the movement (MT) or both, and how this differs in children with DCD compared to Typically Developing Children (TDC).

2. Methods

2.1 Participants

Ten children (Males=6) aged 7-10 years of age (M= 8y 3m; SD=±17 months) who met the research criteria for DCD and 10 children (Males = 5, M= 8y 4m; SD=± 17 months) who are age matched (±0.3m) to the children with DCD participated in the study. All children except two (one from each group) were right handed, as determined by which hand they preferred to use to write their name. Group membership was decided using a similar procedure to that adopted in our earlier work which follows a two-step procedure to identify children with a movement difficulty (see Sugden & Wright, 1998) and is in line with the Leeds Consensus Statement (Sugden, Chambers, & Utley, 2006; http://www.dcd-uk.org/consensus.html).

Two local primary schools were approached and invited to take part in the study. Classroom teachers from these schools identified children who they considered to have poor movement skill for their age (i.e. they demonstrated difficulty with handwriting, using classroom instruments such as scissors, pencils etc and/or physical education activities (Criterion B DSM-IV diagnostic criteria). They were also asked to identify a child of the same gender and age (within 6 months) who did not demonstrate poor movement skills. All children were then assessed using the Movement Assessment Battery for Children-2 (MABC-2; Henderson et al., 2008; Criterion A). Children comprising the DCD group all scored at the 9th percentile or lower on the performance section of the MABC-2 (six at or below the 5th percentile), all 11 typically developing age-matched children (TDC) scored above the 50th percentile (10 at or above the 63rd; 5 at or above the 75th). Parents were asked to confirm that their child had no known visual, auditory, learning, musculoskeletal or neurological disorder (Criterion C). As all children were recruited from mainstream primary schools they were assumed to have IQ levels within the normal range (Geuze et al., 2001) and where possible teachers confirmed that each child's reading age was in line with their chronological age (Criterion D). The screening procedure and experimental paradigm was approved by a University ethics committee and was performed in accordance with the declaration of Helsinki. Each child's parent provided informed consent, and each participant gave informed assent prior to participation.

2.2 Apparatus

All children sat on a chair at a custom built RT board table (115cm x 60cm); which were both height adjustable. On the board was a start button which was positioned in line with the sternum and a semi-circle of three response buttons (12mm in diameter) which were 20cm from the start button. Directly behind each response button was a speaker embedded in the table which housed a single embedded red light emitting diode (LED; 5mm in diameter).

These audiovisual targets were labelled T1 (far left), T2 (midline) and T3 (far right). The speakers emitted a 65db burst of broadband noise. The presentation of stimuli was controlled by a laptop using a custom written program. Kinematic data for aiming was recorded using a 5 camera Proreflex (Qualisys, Gothenburg, Sweden) motion capture system. Reflective markers (12mm) were placed on the participants' wrist and index finger of both hands and aiming movements were sampled at 120Hz.

2.3 Procedure

Prior to each individual's data collection phase participants were given a maximum of 5 warm up trials to ensure that they could complete the task, understood the instructions and so that they were familiar with the experimental set up. Furthermore these trials served to establish if the children could see the LED's and could hear the sound emitted from the speakers. None of the children reported difficulties seeing or hearing the targets and all responded in the familiarisation trials by locating and pressing the correct response target button. All could exert appropriate force on the home and target button.

Participants sat with their feet flat on the floor and hips and knees at 90 degrees in front of the RT board. All participants completed a choice (CRT) reaction time task, with both the dominant and non-dominant hands. Participants were asked to move their finger from the start button to the relevant target button as quickly and as accurately as possible in response to one of three different stimuli: 1) unimodal visual condition (VO; just the LED) 2) unimodal auditory condition (AO; just the broadband sound) 3) Bimodal condition (AV); both light and sound were presented spatially and temporally coincidently). Order of stimuli condition (visual, auditory and bimodal) was blocked and counterbalanced.

The order of hand used to complete the task (dominant and non-dominant hand) was counterbalanced across participants. The experimenter started recording using Proreflex and the video camera and asked participants to place their index finger on the start button. This triggered the RTboard and after a short delay the one of the targets either lit up, emitted the broadband sound, or both. Participants were told to react and move as quickly as possible to press the button next to the target before returning to the start button to trigger the next trial. The time delay between pressing the start button and the target coming on was randomised between 0.5s and 1.5s. Participants completed 15 trials in each stimulus condition; 5 trials to each target (so a total of 45 trials per hand). Proreflex recorded the 15 trials from each stimulus condition block together as one recording, which was later split into the separate trials for analyses.

2.4 Dependent measures and Analyses

For each child, mean values were recorded for each dependent variable. Reaction time (RT) was acquired offline through the RTboard software and was measured by the time between target display onset and finger lift off from the start button. All raw kinematic data was converted into three dimensional coordinates (x,y,z) and then filtered using a lowpass Butterworth filter with a cutoff frequency of 10hz and analysed using Visual3D (C motion software). Start and end of hand movements were defined as moving at >5cm/s for 10 frames and <5cm/s for 5 frames respectively. The following four kinematic measures were recorded: Movement Time (MT): the time from the start to the end of the movement, Peak Velocity (PV): the highest recorded velocity of the index finger marker during the aiming task, Proportion Deceleration Time (propDT): Time from peak velocity to the end of the movement divided by the total MT, and Path Length (PL): the total resultant distance the index finger travels from start button to target location button.

All dependent variables were analysed using a mean calculated from the 5 trials to each button in each stimulus condition, for each hand, for each participant. These values were then included in separate repeated measures ANOVAs with a between subjects factor of group (DCD, TDC) and within subjects factors of Stimulus (VO, AO, AV), Hand (dominant, non-dominant) and Target (T1, T2, T3). When there were significant main effects, means were compared post hoc using pairwise comparisons with Bonferonni adjustments. All significant interactions were further explored using appropriate inferential statistics. Measures of effect size (η^2) were also calculated and all significance levels were set at $p \leq .05$.

3. Results

3.1 Reaction Time

Figure 1 clearly shows that children with DCD were significantly slower (574ms) to react than TDC (450ms) [$F(1,18) = 6.749$; $p < 0.05$, $\eta^2 = 0.27$]. The main effect of stimulus [$F(1.17, 21.05) = 9.926$; $p < 0.001$, $\eta^2 = 0.36$] shows that RT's were significantly quicker to the AV stimulus (447ms) when compared to VO (592ms) or AO (497ms) conditions (for both $p <0.01$) which were not significantly different from each other. A main effect of target [$F(2,36) = 3.955$; $p < 0.05$, $\eta^2 = 0.18$] showed that movements to T2 (538ms) were characterised by longer RTs than movements to T3 (488ms) ($p<0.05$) with no difference between T1 (511ms) compared to T2 or T3 (see Fig. 1). There was no main effect of hand [$F(1,18) = 0.349$; $p = 0.562$, $= 0.019$] and no significant interactions.

Figure 1 about here

3.2 Movement Time

As expected, a main effect of group [$F(1,18) = 10.093$; $p < 0.01$, $\eta^2 = 0.36$] showed that children with DCD exhibited significantly longer MTs than TDC (DCD=486ms;

TDC=434ms; see Fig. 2a). There were no other main effects. There was a significant interaction of hand and target [F(2,36) = 8.562 ; $p < 0.01$, η^2 =0.32], and paired samples t-tests showed that the dominant hand exhibited a shorter MT than the non- dominant hand but only to T3 ([t(19) = -3.012 ; $p < 0.01$] and T2 [t(19) = -2.188 ; $p < 0.05$]. Furthermore, repeated measures ANOVAs on the hands separately (with stimuli collapsed) showed main effects of target for both the dominant [F(1.33, 25.25) = 7.230 ; $p < 0.01$, η^2 = 0.28] and non-dominant [F(2,38) = 3.582 ; $p <0.05$, η^2 = 0.16] hands. While there were no significant simple effects for the non-dominant hand, significantly longer MTs were noted for the dominant hand to T1 compared to T3 ($p < 0.001$). No further interactions emerged

3.3 Peak Velocity

There was no main effect of group or hand but there was a main effect of stimulus [F(2,36) = 3.482 ; $p < 0.05$, η^2 = 0.16] with PV being greater in movements to the AV targets than to the AO and VO targets (AO = 1.142, VO = 1.170, AV = 1.183) (however simple effects showed all comparisons failed to reach conventional levels of statistical significance) (Fig 2b). A main effect of target [F(2,36 = 9.026 ; $p < 0.01$, η^2 = 0.33] showed that the PV of movements to T3 (1.213) were significantly faster than to T1 (1.140) and T2 (1.141) ($p < 0.01$) which were not significantly different from each other. A significant interaction of target and hand emerged [F(1.19, 21.38) = 13.529; $p < 0.01$, η^2 = 0.43] (see Fig. 2c). Paired samples t-tests on the dominant vs the non-dominant hand at each target (collapsed across stimulus and group) showed the PV of the dominant hand was quicker than the non-dominant hand to T3 [t(19) = 3.916 ; $p < 0.01$], whereas the reciprocal effect occurred in reaches to T1 [t(19) = -2.910; $p < 0.01$]. There was no difference between the hands when moving to T2.

Repeated measures ANOVAs on the hands separately (with stimulus and group collapsed) showed main effects of target for both hands (dominant [F(1.44, 27.44) = 21.72; p

< 0.001, $\eta^2 = 0.53$]; non-dominant [$F(1.55, 29.43) = 4.472$; $p < 0.05$, $\eta^2 = 0.19$]). PV to T3 was greatest when the dominant hand was used (T1 vs T3= $p<0.001$; T2 vs T3=$p<0.001$] and PV to T3 being lowest when the non-dominant hand was used (T1vsT3=$p<0.077$).

Insert figure 2 about here

3.4 Proportion of the movement spent decelerating

While the main effects of group, target and hand failed to reach statistical significance, there was a main effect of stimulus [$F(2,36) = 5.361$; $p < 0.01$, $\eta^2 = 0.23$]. Post hoc analysis showed that there was a significantly larger deceleration phase (propDT) when moving to the VO stimulus (M= 0.712), smallest to the AO stimulus (M= 0.694) ($p<0.05$), with movements to the AV stimulus being in between (M= 0.702) (see Fig. 2d).

There was also a significant group x hand interaction [$F(1,18) = 7.214$; $p < 0.05$, $\eta^2 = 0.29$]. But more interestingly, a significant group x hand x stimulus interaction [$F(2, 36) = 3.689$; $p < 0.05$, $\eta^2 = 0.170$. For the dominant hand, independent t-tests revealed that the TDC children spent significantly less time decelerating than the DCD children when moving to the AO stimulus [$t(18) = 2.786$; $p < 0.01$], and AV stimulus [$t(20) = 2.039$; $p < 0.05$] but not the VO one ($p>.05$). There were no group differences in movements to any of the stimuli for the non-dominant hand. A repeated measures ANOVA on the dominant hand showed a significant main effect of stimulus for the TDC group [$F(2,18) = 10.977$; $p < 0.01$, $\eta^2 = 0.549$] but not the DCD group. Pairwise comparisons with Bonferroni corrections show this was driven by significant differences between VO and AO ($p<0.01$). For the nondominant hand no main effect of stimulus emerged for the TDC group or DCD groups.

3.5 Path Length

A main effect of group emerged [$F(1,18) = 6.229$; $p < 0.05$, $\eta^2 = 0.26$]. Children with DCD (mean = 25.6cm) produced longer path lengths than TD children (mean = 24.2cm) (see Fig. 2e). No further main effects or interactions emerged.

4. Discussion

The purpose of this study was to investigate whether children with DCD and their AMC gain a behavioural advantage when reacting (planning) to and moving (execution) to a stimulus that was bimodal in nature (light and sound) compared to stimuli that were unisensory (light or sound alone). Furthermore, we were interested in whether there were differences between the groups with respect to planning and movement parameters with respect to type of stimulus. To our knowledge, this is the first study that has examined how a multisensory stimulus affects reaction time in children with DCD, and movement execution in both children with DCD and typically developing children (TDC).

In line with past research (Henderson, Rose and Henderson, 1992; Hyde and Wilson, 2011; Debrabant et al., 2013), a main effect of group also showed that children with DCD were still slower at reacting to the stimuli than TDC. However, when reacting to the AV stimulus the RT’s of the children with DCD were equivalent to those observed in TDC when reacting to a unisensory stimuli. Overall, the reaction time data supports the notion that children with and without DCD benefit from multisensory information when planning movements (Brandwein et al., 2011). As expected, both groups of children produced faster RTs to the bimodal stimulus (AV) (e.g. main effect of stimulus, see fig 1), and the relative difference in RT between the AO and AV stimuli is similar to that reported by Brandwein et al., (2013) in TDC 7-10 years of age. It is suggested that multisensory neurons are involved in the generation of efferent motor commands to (indirectly) control the musculature of the eyes e.g. gaze control (Stein and Stanford, 2008). Past research has shown that saccadic eye movements to spatially aligned visual and auditory stimuli have reduced RT's and increased accuracy over those generated by unisensory stimuli (Frens et al., 1995). Although not directly tested this could imply that initiating eye movements towards a visual target is faster when an auditory stimulus occurs at the same time and from the same place (spatially and temporally coincident). It could be that by using the auditory stimulus in combination with a visual stimulus (AV) the participants were provided with additional spatial information, via the dorsal auditory pathway (Rauschecker and Tian, 2000), about the intended target for the preparation of action, thus reducing their RT's. Furthermore, video games which used use multisensory information have also be found to increase attention abilities in people with dyslexia (Franceschini et al., 2013) and improve dynamic balance in children with DCD (Jelsma et al., 2014). Thus the role multisensory information might play during allocation of attention as part of physical therapy for example, should be explored.

The effect that a bimodal stimulus has on movement execution parameters revealed a different set of data, and differences between groups were more apparent. Children with DCD displayed significantly longer MTs and PLs irrespective of target stimulus, or target location (See Figs 2a and e) than the TDC (Astill, 2007; Hyde and Wilson, 2011; Biancotto et al., 2011). These data could be explained by the suggestion children with DCD have difficulty forming efficient muscles synergies, resulting in impaired timing of muscular and motion dependent torque peaks (Konczak et al., 1997), with difficulties with impaired neuronal firing of the muscles having been cited previously as a core deficit of children with DCD (Biancotto et al., 2011).

There were no significant differences between the groups with respect to PV, and data showed that overall children, irrespective of group, reach higher peak speed when moving to the audiovisual stimulus than the others (see Fig 2B). PropDT was also affected by the nature of the stimuli and overall children spent more time decelerating to the VO target compared to AO and AV target, with no difference between the latter (fig 2D). Interestingly, the TDC also had shorter deceleration phases when moving towards the stimuli that emitted sound (AO and AV), but only with the dominant hand. This latter observation suggests that at least in tasks where the initial target location is unpredictable, TDC can make use of auditory information and may have to rely less on visual feedback once the movement is underway, but only when using their dominant hand.

Evidence suggests that the dorsal auditory pathway mediates the transformation of auditory signals into a form that constrains motor output and can be conceptualised as the ‘do’ pathway for auditory information (Warren, Wise and Warren, 2005). Our data suggests engaging the dorsal auditory pathway for movement control (using an AO or AV stimulus) in children who are typically developing could be beneficial. However, for children with DCD there was no such benefit and it may be that children with DCD have an impaired sensitivity of the auditory dorsal pathway, as is has been observed in visual-dorsal stream (Sigmundsson et al., 2003; Tsai et al., 2008). This global deficit of the dorsal sensory processing streams could explain the difficulties children with DCD have with on-line movement correction, and feedback control (Wilson & McKenzie, 1998).

Brandwein et al., (2011) reported that multisensory facilitation of behaviour was still immature in children aged 7-to 9-years-old and doesn’t reach mature levels until 13-16 years of age. Furthermore, for children with DCD not only has previous research suggested that children with DCD have deficits with sensorimotor integration (Mon-Williams et al., 1999; Sigmundsson et al., 1997), but Bair et al’s., findings also support the view that optimal multisensory integration is vulnerable in children with DCD. Thus, it could be reasonable to assume that with an older group of children with and without DCD, further behavioural advantages to reacting and moving to a bimodal or auditory only stimulus could emerge.

Here we provide the first evidence that both children with and without DCD do gain a behavioural advantage when reacting (planning) to a bimodal stimulus. Furthermore, we provide preliminary evidence that TDC do benefit from a either audiovisual or auditory information during execution of a simple aiming movement, but that children with DCD do not. While performance did not deteriorate in bimodal conditions, compared to the available data on adults (e.g. Giray & Ulrich, 1993; Plat et al., 2001) our data suggests multisensory integration to support movement control could be slow to develop in children, and potentially impaired in children with DCD (Bair et al., 2012), however this requires further exploration. Given that children are continually bombarded with stimulus input, and that the integration of multisensory information is critical to coordinated behaviour, more work should focus on understanding the optimisation of multisensory integration in children with and without DCD and how it can then be incorporated into movement training and/or rehabilitation strategies.

Competing interests

The authors declare that they have no competing interests.

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Figure Captions

Figure 1. RT

Reaction time (ms) per group and stimulus condition for both the dominant and the non-dominant hand (target collapsed). Shaded bars represent the DCD group, clear bars represent the TDC group.

Figure 2. MT, PV, propDT, PL

(A) Movement Time (ms), (B) Peak Velocity (mm/s), (D) Proportion of the movement spent decelerating, and (E) Path Length (cm) per group for both the dominant and non-dominant hands to all stimuli (target collapsed). Shaded bars represent the DCD group, clear bars represent the TDC group. Figure (C) shows the hand x target interaction for Peak Velocity (mm/s). Diagonal chequered bars represent the dominant hand, filled bars represent the non-dominant hand.