The Multiple Process Model of Goal-Directed Aiming/Reaching: Insights on Limb Control from Various Special

Populations

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Abstract

Several years ago, our research group forwarded a model of goal-directed reaching and aiming that describes the processes involved in the optimization of speed, accuracy, and energy expenditure (Elliott et al. 2010). One of the main features of the model is the distinction between early impulse control, which is based on a comparison of expected to perceived sensory consequences, and late limb-target control that involves a spatial comparison of limb and target position. Our model also emphasizes the importance of strategic behaviors that limit the opportunity for worst-case or inefficient outcomes. In the 2010 paper, we included a section on how our model can be used to understand atypical aiming/reaching movements in a number of special populations. In light of a recent empirical and theoretical update of our model (Elliott et al. 2017), here we consider contemporary motor control work involving typical aging, Down syndrome, autism spectrum disorder, and tetraplegia with tendon transfer surgery. We outline how atypical limb control can be viewed within the context of the multiple process model of goal-directed reaching and aiming, and discuss the underlying perceptual-motor impairment that results in the adaptive solution developed by the specific group.

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Preamble

In 2010, our group published a theoretical paper in which we introduced a new model of the optimization of limb control in speeded goal-directed aiming and reaching (Elliott et al., 2010). The model draws heavily on Woodworth's (1899) two-component description of limb control, as well as the *optimized submovement model* (Meyer et al. 1988). Central to our model is an important distinction between what we term "impulse control" and "limb-target control". Following Woodworth (1899) and Meyer et al. (1988), limb-target control involves a discrete corrective process that occurs as the limb approaches the target area. It requires an evaluation of the relative spatial positions of the limb and the target that often entails a second acceleration of the limb because goal-directed aiming movements are typically planned to slightly undershoot the target position (Elliott et al. 2001; Engelbrecht et al. 2003; Worringham 1991). In contrast, the term impulse control describes an early process that regulates the limb as it moves away from the home position. It is based on the comparisons of perceived limb direction and velocity to sensory expectations about these features of the movement. These expectations are part of an internal action model that also includes information about motor outflow (Wolpert and Ghahramani 2000). A mismatch between early proprioceptive and visual feedback and expected sensory consequences leads to a graded regulation of muscular force during the primary acceleration and deceleration phase of the movement. In past models, this phase of the movement was thought to be ballistic in nature (Keele 1968; Meyer et al. 1988; Woodworth 1899).

In Elliott et al. (2010), we outlined the specifics of the multiple-process model and the supporting evidence. As well, we provided an overview on how our model might be used to understand movement difficulties and/or differences in a number of special populations. Recently, our group published a paper in which we review and update theoretical aspects of our model based on work since 2010 (Elliott et al. 2017). However, we did not include reference to studies involving any special populations. Our intent is to fill that gap with the current paper. In this context, we provide a brief overview of our model, followed by a more detailed account of how the model can be used to understand rapid limb control in a number of specific special populations. By focusing on the micro level of movement substructure in a variety of experimental contexts, we aim to identify the altered perceptual-motor processes that lead to development of adaptive solutions by these specific special groups.

Multiple Process Model of Goal-Directed Aiming/Reaching: A Brief Overview

Similar to the optimized submovement model (Meyer et al. 1988), our model posits that human performers plan their aiming/reaching movements with consideration for the inherent variability associated with movement execution. Movements

of greater speed and/or larger amplitude require greater muscular force than slower and/or smaller amplitude movements. Greater absolute muscular force is associated with greater force variability and therefore increased spatial variability compared to less forceful movements (Schmidt et al. 1979). When planning a series of movements to the same target, the performer attempts to increase the efficiency of their movements by striking a compromise between moving quickly and executing movements that will hit the target on a large proportion of the aiming/reaching attempts. This strategy is adopted because an initial movement trajectory that ends outside of the target boundary will require one or more corrective submovements. These corrections take additional time to complete, and require an additional expenditure of energy. Therefore, an increased reliance on corrective movements to minimize spatial variability could reflect inefficient motor control.

Meyer and colleagues (1988) held that, for any given target context (i.e., target size and movement amplitude; see Fitts 1954), there is an optimal distribution of primary movement endpoints centered at the middle of the target (see also Slifkin and Eder 2017). Ideally the majority of this distribution falls within the boundaries of the target. However, the tails of the distribution will fall outside of the target boundaries and the aiming/reaching attempts associated with these two portions of the distribution will require a corrective submovement for the limb to hit the target. In the case of the near tail, this correction will be a secondary acceleration-deceleration. An error associated with the far tail will require a reversal in the direction of the limb movement (i.e., a negative velocity situation). These ideas make sense unless one rejects the assumption that second accelerations and movement reversals are equally time consuming. In our work, we have shown that target overshoots, requiring a reversal, take more time to complete than corrections associated with an initial target undershoot (Elliott et al. 2004; see also Oliveira et al. 2005). Reversals also require greater energy expenditure (Elliott et al. 2017) because the limb travels a greater distance and the system must overcome the inertia of a zero-velocity situation at the point of the reversal. This change from a positive to negative velocity in the primary direction of the movement also involves a change in the role of the agonist and antagonist muscle groups requiring greater involvement of the latter. For this reason, the multiple process model holds that the distribution of primary movement endpoints is typically situated short of the target center. The empirical evidence associated with the spatial substructure of manual aiming movements is consistent with our model (Burkitt et al. 2015; Carson et al. 1992; Elliott et al. 1991, 2004, 2014; Elliott and Hansen 2010; Grierson and Elliott 2009a, 2009b; Heath 2005; Lyons et al. 2006; Mendoza et al. 2006; Roberts and Grierson 2019; Worringham 1991).

Our model holds that the degree of strategic primary movement undershooting depends on the endpoint variability of the primary movement. Thus, more forceful movements to far targets will be associated with greater primary movement undershooting than less forceful movements to near targets (see Elliott et al. 2001, 2004, 2010, 2017). Likewise movements

to small targets, that have an increased chance of missing, typically generate greater primary movement undershooting than larger targets (Roberts 2020). If the performer is able to reduce endpoint variability due to improved force-time specification over practice, then the mean of the primary movement endpoint distribution will move closer to the target. The strategy is simply to keep the proportion of trials that need to be corrected with a limb reversal very low (Elliott et al. 2004). This strategy will also reduce the magnitude of any corrections that need to be made. In this paper and elsewhere (e.g., Elliott et al., 2010, 2017; Roberts et al. 2018), we often refer to strategic undershooting as a "play-it-safe strategy". Although it may literally be the case if one is working with a circular saw or reaching for a full glass of beer (i.e., to avoid a spill), more broadly "play-it-safe" means avoiding a worst-case outcome in terms of movement time and energy expenditure. As an example, an initial target overshoot that requires a reversal will take more time and energy to correct than an initial target undershoot.

Consistent with our notion that not all error corrections are equal in terms of time and energy expenditure are findings from a number of studies in which we have systemically manipulated the cost of an overshoot compared to an undershoot. For example, Lyons et al. (2006) demonstrated that performers undershoot the target center to a greater extent when aiming downward than when moving upward or horizontally. This outcome occurs because a target overshoot when moving downward requires a corrective movement against gravity and thus entails greater temporal and energy costs (for more detailed description of this strategic phenomenon see also Burkitt et al. 2017 and Elliott et al. 2014). In addition, aiming movements in which there is greater mass associated with the aiming limb undershoot more than movements involving an effector of lower mass (Burkitt et al. 2015). Once again, this happens because greater limb mass is associated with even greater time and energy expenditure for movement reversals (i.e., even more inertia to overcome at the point of the reversal).

Our model also holds that prior knowledge about the availability of feedback impacts movement planning and, thus, the characteristics of the primary movement trajectory over multiple trials. That is, in order to make full use of visual feedback, the performer needs to know that it will be available for online control of the limb trajectory. When there is uncertainty about the availability of feedback the performer prepares their movement for the worst-case (or no vision) scenario. Specifically, they take more time to prepare their movements, produce more symmetric movement trajectories and undershoot the target position to a greater extent with their primary movement (Burkitt et al. 2013; Hansen et al. 2006; Khan et al. 2002; see Elliott et al. 2017 for a full review).

Central to the multiple process model of limb control is the concept of impulse control. Specifically, our model holds that the initial distance-covering phase of the movement (i.e., the primary movement) is amenable to online proprioceptive and visual regulation. This notion is based on several decades of work that shows changes and/or differences in the primary

movement trajectory that result from perturbations to the limb movement or the perceived limb movement that impact the endpoint of the primary movement (Elliott et al. 1991, Elliott et al. 1999, 2014; Grierson and Elliott 2009a; Hansen et al. 2006; Heath et al. 1998). Our model holds that impulse control can begin very early in the movement (i.e., in as little as 80 ms after movement initiation). It is based on a comparison of early limb direction and velocity with expectations about the sensory consequences (i.e., both visual and proprioceptive) for that particular movement. These expected sensory consequences and information about anticipated motor outflow are part of an internal representation/model of the movement that is formed at the time of movement planning. The model becomes refined over repeated practice with the same type of movement and, as mentioned earlier, also takes into consideration prior knowledge about what sensory information may or may not be available for impulse control and limb-target control. With repeated practice at the same class of aiming/reaching movement, impulse control becomes more precise because movement planning and the internal model are more precise. Thus, endpoint variability and strategic behavior associated with the central tendency of the primary movement endpoints can change due to both more precise force-time specification during movement execution and improved impulse control. These improvements eventually reduce the necessity for corrective submovements during limb-target control, which, due to their discrete nature, are inherently less time and energy efficient than impulse control.

Special Populations and Atypical Upper Limb Control

When we initially presented our multiple-process model of goal-directed aiming, we examined the breakdown of optimal speed-accuracy processes in a number of special populations (Elliott et al. 2010) to determine whether the sensory-motor problems associated with each of these groups were consistent with aspects of our theoretical position. It also provided us with an opportunity to isolate specific strategic and/or biological differences in these groups that might be amenable to instructional or environmental interventions. Over the intervening years, we have continued to investigate the effect of age and pathology on optimal speed-accuracy performance. Here, we revisit our evaluation of rapid goal-directed aiming/reaching in typical aging, autism spectrum disorder (henceforth autism) and Down syndrome. We also review some new empirical work involving people with C6 spinal cord injuries who have undergone tendon transfer surgery. Because our model deals with the optimization of speed, accuracy and energy expenditure in goal-directed aiming and reaching, we have limited our review to studies dealing with these sorts of motor activities. Exceptions to this general rule occur only when the study provides insight into issues such as feedback utilization and feedforward control that have relevance to our model.

Typical Aging

The typical aging process is associated with a number of physical and cognitive changes (Salthouse 2009). Of interest here is the progressive deterioration in the speed at which goal-directed aiming and reaching movements are executed (e.g.,

Temprado et al. 2013). The majority of extra time required to complete goal-directed movements appears to be associated with the time after peak velocity, especially the time between peak deceleration and the end of the movement (Cooke et al. 1989; Darling et al. 1989; Goggin and Stelmach 1990; Welsh et al. 2007). With respect to our model, this portion of the movement trajectory is associated with limb-target control. Several studies have shown that the primary movements of older adults undershoot the target position to a greater extent than the primary movements of younger participants (Ketcham et al. 2002; Poletti et al. 2015; Pratt et al. 1994; Van Halewyck et al. 2014) and that older performers exhibit a greater number of corrective submovements during limb deceleration than younger adults (Lyons et al. 1996).[1]

Given these sorts of kinematic differences in the movement trajectory between the young and the old, it has been suggested that older adults are more feedback-dependent than younger adults (e.g., Lyons et al. 1996). One notion is that feedback dependency stems from an age-related inability to produce reliable muscular forces. This idea is based on findings by Galganski et al. (1993) in which older participants exhibited greater variability than younger participants in producing various submaximal levels of isometric force with a finger abduction task. Vaillancourt and Newell (2003) found similar results for static submaximal force production, and that greater force production variability was not associated with the processing of visually displayed feedback about force production (Sosnoff and Newell 2006).

In contrast to static force production, when participants were required to produce force rapidly to move a cursor into a target-force bandwidth (i.e., a Fitts' aiming task), older participants exhibited greater variability in time to peak force but similar force production variability compared to younger adults (Temprado et al. 2017). Moreover, there were no differences in the end-point variability between young and old groups within the target-force area. Thus, the greater timing variability in older participants could reflect an adaptive feedback utilization strategy designed to bring the cursor into the target area. In a 3-dimenional target-aiming task that involved dynamic movement of the limb from the home position to a target, Welsh et al. (2007) found similar patterns of temporal and spatial variability in younger and older adults. Therefore, as the aiming/force production task becomes more natural, age difference in variability between the young and the old tend to disappear.

Given that any variability differences between young and older adults are usually diminished by the end of the primary movement, it is unlikely that an increase in the number of corrective submovements with age is due to force parameterization and thus an over reliance on limb-target control. In addition, aiming differences between older and younger adults do not appear to depend on the availability of visual feedback (Van Halewyck et al. 2014) or the use of saccadic eye movements for late limb control (Van Halewyck et al. 2015). Based on the distribution of the primary movement endpoints of older adults, we have suggested that a more likely explanation for age-related differences in aiming kinematics is that older adults adopt a pronounced "play-it-safe" strategy during the planning stage of movement (Elliott et al. 2010). These

strategies are generally functional unless there is some cognitive impairment associated with the aging process (Poletti et al. 2017). As mentioned earlier, a "play-it-safe" approach to movement execution minimizes the probability of worst-case outcomes that involve greater time and energy expenditure. This approach is also associated with the avoidance of accident and injury that could result from overshooting a target (Elliott et al. 2009). For example, a reach that overshoots the target could knock over a glass of beer or, in the case of a circular saw, result in a grave injury.

Poletti and colleagues (2015; Poletti et al. 2016) examined strategic aiming behavior in young and older adults using a Fitts' aiming protocol. Consistent with previous research, they found that older adults exhibited more corrective submovements than younger adults. Poletti et al. (2015; see also Sleiman-Malkoun et al. 2013) suggested that older adults used a smaller repertoire of strategic behaviors than young adults. The younger adults exhibited undershooting on some trials, but also many more aiming trials comprising only a primary movement (i.e., immediate landing on the target). Although these researchers associated each type of kinematic profile with a particular strategic approach to the task, it is likely that stochastic spatial variability yielded different outcomes based on one overriding strategy. Although the absence of a spatial variability measure in the Poletti and colleagues (2015) study makes it difficult to confirm, we suggest that older adults adopted a strategy to undershoot the target center with the primary movement in order to reduce the probability of an overshoot (i.e., older adults never overshoot the target) combined with a subsequent reversal in limb direction. Conversely, younger adults attempted to direct their primary movement closer to the target center, which resulted in fewer trials with corrective submovements, but also increased the probability of more overshooting and directional reversals (i.e., younger participants overshoot the target on 4% of all trials; cf. 0% for older participants; Poletti et al., 2015). Thus, rather than having a larger repertoire of strategic behaviors, younger adults produce a distribution of primary movement endpoints that more closely approached the near boundary of the target. While this single strategy resulted in more target hits with the primary movement, it also resulted in some target overshoots that required a reversal in movement direction to hit the target (i.e., 4%).

In another study designed to examine strategic behavior and aging, Bennett et al. (2012) used an adaptation of the Lyons et al. (2006) vertical aiming protocol to examine the "play-it-safe" hypothesis. Late middle-aged participants (under 65 years) and older participants (over 65 years) made rapid aiming movements to vertically arranged targets. Similar to Lyons et al. (2006), both groups undershot the target position with their primary movement to a greater extent when aiming downward than upward. There was also greater spatial and temporal variability associated with the downward primary movements. Correlational findings collapsed over group indicated that increasing age was associated with both shorter amplitude primary movements and larger amplitude and longer duration corrective submovements. Taken together, these

findings indicate that older and middle-aged adults adjust their aiming trajectories when moving downward to avoid costly corrective submovements against gravity. They also suggest that this "play-it-safe" strategy is more pronounced in older performers.

This conservative approach to manual aiming appears to be less evident in older adults that are physically active than those that are sedentary. For example, in a study on discrete aiming, Van Halewyck et al. (2015) showed that the movement times of sedentary older adults only (*cf.* active older adults) were longer than the movement times of young participants. As in previous work, these longer movement times were associated with a shorter primary movement and more time spent with limb-target corrective processes. Interestingly, both active and sedentary older adults exhibited smaller amplitude primary saccades than their young counterparts, although this difference did not translate to shorter limb movements in the active older participants. At least for sedentary older adults, it would seem that a target undershooting strategy occurs in both eye gaze and upper-limb aiming. Perhaps this is not surprising given that in order to provide the most precise visual information, the eyes must move to where the hand intends to be (Helsen et al., 1998).

Although active older adults exhibited a pronounced advantage for accuracy-constrained discrete aiming, their performance was more similar to sedentary older adults for reciprocal aiming when a metronome was used to regulate movement speed (Van Halewyck et al. 2015). Specifically, both active and sedentary older adults tended to undershoot and miss the targets more often than young adults. Thus, it appears that when movement speed was constrained by the task, both active and inactive older participants exhibited greater spatial and temporal variability and, subsequently, demonstrated greater endpoint error than younger adults. That said, contrary to the majority of previous work on discrete aiming, there was a relatively high percentage of target overshoots, which was most pronounced in the sedentary older adults. This group also exhibited the greatest temporal variability at peak acceleration and peak velocity. This between-protocol difference for older active adults suggests that the aiming strategy of slowing down and undershooting the target in self-regulated aiming is adaptive. Thus, the impact of age on performance is most evident when the task demands limit strategic behavior.

In other recent work, Van Halewyck et al. (2015) had older and younger adults perform discrete aiming under different speed and accuracy instructions. Older adults were shown to be quite capable of performing rapid primary aiming movements under speed instructions, but they were more likely to adopt a "play-it-safe" strategy when accuracy was paramount, or when they voluntarily selected the relative importance of speed and accuracy (i.e., control condition). Specifically, older adults exhibited longer movement times with trajectories characterized by shorter primary movements, and a greater degree of discrete limb-target regulation late in the movement. This was in contrast to young adults, who modified

their aiming behavior when instructed to focus on accuracy compared to the control condition, potentially confirming the suggestion that age influences the repertoire of strategic aiming behaviors (Poletti et al. 2015).

Taken together, these studies suggest that, compared to young adults, sedentary older adults adopt a limb regulation strategy that emphasizes accuracy over speed. This approach to goal-directed aiming/reaching reduces the impact of movement errors that require extra time and energy to correct. Perhaps of greater practical relevance is the finding that lifestyle may be just as important as age in predicting the strategic approach and thus movement outcome in rapid goal-directed reaching (Van Halewyck et al. 2014, 2015).[2]

Down Syndrome

Children and adults with Down syndrome take more time to initiate and complete goal-directed aiming movements than their chronological age counter-parts from the general population (Chen et al. 2015; Elliott et al. 2006; Gimenez et al. 2017; Hodges et al. 1995; Lawrence et al. 2013; Vimercati et al. 2012). This perceptual-motor slowness is particularly evident when the accuracy demands of the movement are high (Hocking et al. 2011; Lam et al. 2009). As well, adults with Down syndrome take more time between movement components, than do adults without Down syndrome, when performing reciprocal aiming movements (Lam et al. 2009) and multi-component aiming movements involving reversals (Reilley et al. 2017), but not when performing sequential movements with only two components (Lawrence et al. 2013).

The limb trajectories of adults with Down syndrome are typically characterized by lower peak velocities and multiple discontinuities in the deceleration phase of the movements (Chen et al. 2015; Elliott et al. 2006; Hodges et al. 1995; Vimercati et al. 2013). Empirical evidence on the awareness of voluntary action, in which the generation of an internal model sets the foundation for anticipatory judgements, indicated delayed responses in Down syndrome much akin to the judgement of external stimulus events (i.e., auditory tone; Obhi et al. 2007). Therefore, we suggested that the primary difficultly of people with Down syndrome is related to forming a stable internal model of the to-be-performed action prior to movement execution (Elliott et al. 2010). This problem with action representation, and movement planning in general, leads to difficulties with feedforward control (including impulse control) that must be rectified late in the movement by discrete feedback-based control (i.e., limb-target control). For example, in a reciprocal aiming task, Hocking and colleagues (2011) showed that adults with Down syndrome demonstrate greater constant and variable errors than typical controls in aiming conditions with the largest amplitudes and target sizes. Considering that movements in these conditions require the greatest muscular forces (i.e., impulses), the authors contend that those with Down syndrome had difficulties applying the appropriate forces at movement onset (and making adjustments using feedforward control), and that online feedback-based control (i.e., limb-target control) was insufficient to minimize endpoint variability. Results from similar studies showed greater hand-

object contact velocities in children with Down syndrome during a reach-to-grasp task (Valvano et al. 2017) and increased movement times for people with Down syndrome in integrated one-arm reversal tasks (Reilly et al. 2017), which are indicative of deficits in force specification and insufficient feedback-based online control.

Further evidence that typically developing individuals and those with DS may differently utilize advance and online information is found in studies where only partial advance information is available (e.g., LeClair et al. 1993; Mon-Williams et al. 2001). In these protocols, participants are presented with pre-movement cues related to the final location of a target or object to be acquired, with these cues differing in terms of the amount of location information provided. For example, the cue was either Complete: specifying an exact location; Partial: providing some general location information (e.g., side of space but not which target); or Null: with no useful location information. Mon-Williams and colleagues (2001) found that, unlike typically developing participants, individuals with DS were unable to take advantage of partial cuing information when reaching to grasp a target block. The authors suggest that fundamental differences in the processes of organizing action for complex movements lead these two participant groups to adopt different movement strategies. For example, when faced with a partial cue that indicates that one of two possible locations will contain the target, typically developing individuals will prepare a movement to the midpoint of those two targets, adjusting the movement online when the exact target location is specified during the reach (e.g., Augustyn and Rosenbaum 2005). Although others (e.g., LeClair et al. 1993) have shown that partial advance information may be useful for participants with DS for the planning and control of simple aiming movements, the majority of the evidence seems to suggest that they are unwilling or unable to implement the same strategy when the movement is more complex (Mon Williams et al. 2001). The likeliest explanation for these differencing group-specific movement strategies is that individuals with Down syndrome are less able, or less willing, to make online corrections to preprogrammed movement trajectories due to a compromised ability to use visual feedback to correct errors at the end of the movement.

More recent aiming studies involving young adults with Down syndrome offer additional support for the idea that this group has difficulty with feedforward control. For example, Vimercati and colleagues (2013b) had participants with and without Down syndrome move a wooden dowel from position-to-position in a 6-target sequential aiming task. As in previous work, the limb trajectories of adults with Down syndrome were characterized by longer movement times, lower velocities and multiple velocity peaks. In addition, their trajectories were more curved than the trajectories of people without Down syndrome, reflecting a less efficient movement path (see also Valvano et al. 2017). The young adults with Down syndrome were also more dependent on proximal than distal musculature to move their arms (i.e., greater movement at the trunk and less at the elbow; see also, Anson and Mawston 2000). With respect to our multiple process model of goal-directed aiming,

the greater use of proximal musculature in people with Down syndrome may reflect less specific and/or precise movement planning. This problem with movement planning may be a characteristic of the syndrome. Alternatively, the tendency to avoid the use of distal muscles may relate to the increased degrees-of-freedom and subsequent variability associated with the involvement of more muscle groups and joints (Bernstein 1967; Kelso 2012). In this case, the added complexity associated with multiple muscle groups is avoided by people with Down syndrome, perhaps because it presents too great a challenge for an already compromised movement planning system (Wolpert and Ghrahramini 2000).

This type of conservative, and likely inefficient, approach to aiming extends to the postural stability of children with Down syndrome when performing standing goal-directed reaches to targets at 80%, 100%, and 120% of arms-length (Chen et al. 2015). For example, Chen and colleagues (2015) showed that children with Down syndrome exhibited less anterior-posterior center of pressure displacement when reaching to a target location out of arms-reach. Considering that this movement context introduced proximal degrees of freedom involving the trunk, this finding suggests that people with Down syndrome are also conservative in organizing proximal joints in movements when shifting the body into unstable positions. Consistent with other work reviewed in this section, Chen et al. (2015) also report that children with Down syndrome perform slower movements that achieve lower peak velocities at smaller proportions of movement time. Since our model contends that greater times spent after peak velocity indicate more time engaged in limb-target control (Hansen et al. 2006), this further highlights the difficulty this group has in using feedforward control (Hansen et al. 2005) and extends this observation into more complex movement dynamics (Chen et al. 2015).

In a follow-up to their 6-target sequential aiming work with Down syndrome, Vimercati and colleagues (2013c) increased the relative complexity of the aiming task by inserting a barrier between targets 3 and 4 in the aiming sequence (see also Vimercati et al. 2013a). This manipulation required participants to increase the vertical component of their aim between the two targets. Although persons with and without Down syndrome adjusted their aiming movements to accommodate the barrier, the participants with Down syndrome increased their vertical motion to a greater degree. Vimercati et al. (2013b) once again concluded that because of compromised feedforward control, persons with Down syndrome were more dependent on feedback for limb control than the control participants. The researchers went on to speculate that participants with Down syndrome were attempting to optimize safety in avoiding the barrier. This interpretation of the results is consistent with a "play-it-safe" strategy to deal with the increased aiming difficulties introduced by the constraint of additional movement demands in a third (vertical) dimension.

Given these differences in movement planning, and with the formation of action representations, it is natural to question how these demonstrated difficulties with feedforward (and impulse) control mediate the way in which individuals

with Down syndrome learn novel motor tasks. Although there is a considerable literature examining general movement learning in individuals with Down syndrome, these studies focus primarily on adaptive training (e.g., Wuang et al. 2011; Lopes et al. 2018) and/or therapeutic, most commonly physical activity, interventions (e.g., Pitetti et al. 2013; Smith et al. 2007; Wu et al., 2008). Relative to this broader literature, there are comparatively few studies that directly examine motor learning in Down syndrome. As both response-produced feedback and feedforward control are considered essential elements in the learning of novel motor tasks, it stands to reason that a greater dependence on feedback for limb regulation may also lead to problems with motor learning. In particular, it has been shown that people with Down syndrome exhibit specific difficulty in learning from action observation (Foti et al. 2018). As well, studies in which we have manipulated vision indicate that proprioceptive feedback may be particularly important for late limb regulation in adults with Down syndrome (Hansen et al. 2005). It can be difficult to draw broad conclusions regarding the effect of Down syndrome phenotypes on motor learning as many of the syndrome-associated effects are task and domain specific. That said, there is evidence that tasks, where learning relies heavily on internally generated feedback (e.g., Hansen et al. 2005), prediction (e.g., Kerr and Blais 1985), timing (e.g., Monteiro et al. 2016), observation (Foti et al. 2018), and task transfer (e.g., Possebom et al. 2016), are all affected adversely in persons with Down syndrome.

Autism Spectrum Disorder

The difficulties autistic individuals[3] experience in social, communicative, and interpersonal contexts (Dawson and Toth 2006; Hill 2004; Lord et al., 2020; Szatmari et al. 1990) has been linked to the sensorimotor processing systems (Cook 2016; Hughes 1996; Mostofsky and Ewen 2011) that modulate the development of skilled motor behavior, and consequently, the effectiveness of internal sensory-motor action models/representations (Mari et al. 2003; Mostofsky and Ewen 2011). For example, autistic individuals are suggested to prioritize the processing of proprioceptive information when learning sensorimotor actions, which might have led to the development of internal action models specific to this sensory domain (Mostofsky and Ewen 2011). Indeed, following a period of sensorimotor practice of an upper-limb, force-field task, autistic individuals were less able to generalize the learned force characteristics when moving to a target goal that only maintained the practiced visual consequences (Haswell et al. 2009). Significantly better sensorimotor generalization occurred when the target movement goal in a transfer condition maintained the practiced proprioceptive consequences of the force-field task. These generalization patterns also correlated with associated social mechanisms, where greater proprioceptive-driven generalization was related to greater difficulties in social interaction (i.e., social communication; social anxiety/avoidance), and imitation/praxis (Haswell et al. 2009).

Differences in the functioning of autistic sensorimotor systems (e.g., proprioceptive-driven generalization) could also underpin behavioral differences in action-observation and imitation learning. We recently found evidence of autism specific internal action model formation in a study that employed a sensorimotor sequence learning task, and a follow-up visual perception discrimination task (Hayes et al. 2016). Although autistic individuals demonstrated more sensorimotor variability (see also Foster et al. 2020a; Hayes et al. 2016) compared to neurotypical individuals during practice, they successfully acquired the sequence timing goal via trial and error practice, and knowledge of results feedback. Data from the visual perception task indicated that both groups accurately discriminated (autism = 75%; control = 76%) the difference between two sequentially presented stimuli that displayed different temporal durations. Follow-up analysis only showed significant correlations between motor timing error, sensorimotor learning, and temporal-discrimination (visual perception) for neurotypical individuals. The finding of no significant relationship between sensorimotor learning and visual perception for autistic individuals suggests that the sensorimotor control processes underpinning internal action model formation may operate differently in autism (Cook et al. 2013; Glazebrook et al. 2006; Lord et al. 2020; Mosconi et al. 2015).[4]

Given the evidence points toward specificity in autistic sensorimotor control processing, we suggest that kinematic examination of the underlying sensorimotor control and learning processes offers an important route for understanding part of the behavioral autism phenotype. Based on the feedforward and feedback processing systems associated with the multiple process model (Elliott et al. 2010, 2017), we have investigated how autistic internal action models operate as part of a feedforward system that controls action-understanding in social contexts, but also the organization, planning and control of goal-directed movements (Foster et al. 2020a, 2020b; Glazebrook et al. 2006, 2008; Nazarali et al. 2009). For example, although higher-level motor planning processes (i.e., grasp height; see Ansuini et al. 2018) are operational in autistic adults (Glazebrook et al. 2008; Nazarali et al. 2009) and children (Ansuini et al. 2018), both these groups (Nazarali et al. 2009; Rinehart et al. 2006) have difficulty generalizing internal action models to new, and unexpected movement goals. These movement planning difficulties are evident across multiple planning tasks, such as imitating atypical novel biological motion (Hayes et al. 2016), and goal-directed aiming to targets with differing levels (e.g., more uncertainty leads to greater executive demand) of location uncertainly (Rinehart et al. 2006). Therefore, motor difficulties are not merely related to problems with executive function in autism (Szatmari et al. 1990), but are specifically associated with central and peripheral sensorimotor processes (Floris et al. 2016; Pillai et al. 2018; Puts et al. 2017; Rinehart et al. 2006) that impact on the efficacy of lower-level control process that guide motor execution.

In terms of movement execution, and compared to neurotypical individuals, motor preparation times can be ~50% greater (Glazebrook et al. 2008; Nazarali et al. 2009), and movement execution times are significantly longer when

performing 3-dimensional (Glazebrook et al. 2006), and 2-dimensional (Hayes et al. 2018), goal-directed aiming movements. When examining the underlying movement trajectory, kinematic data indicated the velocity and acceleration profiles to be elongated with lower peak magnitudes (Glazebrook et al. 2006; Mari et al. 2003). What appears to be most different about the underlying motor control properties of aiming movements is the greater trial-to-trial spatial variability early in the movement (i.e., at peak acceleration and peak velocity; Foster et al. 2020b; Glazebrook et al. 2006, 2009), which is indicative of low efficacy motor planning related to the specification of muscular forces during the impulse control phase of a movement. This increased spatial variability is particularly evident in high-index of difficulty movements (Glazebrook et al. 2006), and is associated with greater variability in muscular force production (Mosconi et al. 2015). Importantly, spatial variability does reduce towards the end of aiming movements as the result of both impulse control and limb-target control (Elliott et al. 2010). This occurs under conditions of full visual feedback and, to a lesser extent, when vision is eliminated upon movement initiation (Glazebrook et al. 2009). These latter findings indicate that feedback-based corrective processes are operational in autistic individuals (Mosconi et al. 2015)[5], and we have shown recently that reductions in spatial variability at peak acceleration and peak velocity occur following a relatively short period of sensorimotor training (Foster et al. 2020a, 2020b).

Although these corrective processes are operational in autistic individuals, they seem to be slower when corrections are made based on visual information. The additional time required to process visual information for limb-target control (Glazebrook et al. 2009; see also Rinehart et al. 2006), could in part could be explained by a less effective planning mechanism (i.e., predictive coding) that is engaged to process prior information for anticipating upcoming goal-directed actions (Ganglmayer et al. 2020). These processing differences are more pronounced in unconstrained environments where a limb movement is performed and controlled in 3 planes, as compared to one and two-plane aiming movements that are planned and executed similar to neurotypical individuals (Zheng et al. 2019). Here, autistic individuals are suggested to depend more on proprioceptive and tactile feedback (see Haswell et al. 2009) when performing more challenging 3-dimensional goal-directed aiming movements. Differences have also been observed in the way that autistic individuals process available visual information during aiming/reaching movements (Campione et al. 2016; Dowd et al. 2012). For example, when a distractor circle was manipulated (i.e., equivalent-sized white distractor circle positioned either 61 mm to the left, or right, of the center of the target circle) during motor planning, neurotypical children demonstrated greater variability in movement preparation time, and took longer to reach peak acceleration during aiming attempts (Dowd et al., 2012). Autistic children exhibited similar movement kinematics in the presence or absence of the visual distractor, thus indicating differences in the way they integrate the visual properties of the environment for motor planning and feedforward sensorimotor control (i.e., sensory input; see Gowen and Hamilton, 2013).

This description of the sensorimotor control processes underpinning reaching behaviors is consistent with data from an experiment where autistic, and non-autistic, children were tasked with executing goal directed movements to intercept and catch projectiles (balls) under different levels of task difficulty (i.e., different ball velocities; Whyatt and Craig, 2013). Compared to neurotypical children, autistic children caught significantly fewer balls, and exhibited comparable movement initiation times in the low and high difficulty task contexts. The fact that they did not accurately modulate motor planning (i.e., they initiated earlier movements) to account for the differing visual task demands suggests an attenuation in the processing mechanism that integrates prospective control based on visual sensory input for motor execution (i.e., perception–action coupling). In addition to differences in movement initiation, they required a greater number of sub-corrective limb movements (i.e., limb-target control) in order to move the limb towards the projectile. This kinematic analysis was suggested to indicate that limb-target control processes operate differently in autism (see also Chen et al. 2019; Forti et al. 2011), which has also been reported when performing a modified Fitts' task (Papadopoulos et al. 2012), a two-choice reach-to-grasp task (Stoit et al. 2013), and a reach-to-ball-drop task (Forti et al. 2011).

Potential differences in sensorimotor integration and issues related to movement planning and control are of particular interest in individuals with autism as this combination of factors may impact upon social behaviors (Cook, 2016; Mostofsky and Ewen 2011). In a social learning context, there has been a great deal of attention paid to action-observation and imitation in autism (Vivanti and Hamilton 2014). Successful imitation requires the encoding and integration of lower-level kinematics and action-goals via a sensorimotor system directly linking perception to action (Prinz 1997). It also involves the engagement of planning processes to control the specification of forces required for initial execution of the to-be-imitated movement pattern. Differences in the imitation of lower-level biological kinematic properties (Hayes et al. 2016; Stewart et al. 2013; Wild et al. 2012) is suggested to be associated with the altered motor control processes and sensorimotor integration (Hayes et al. 2016). For example, low-fidelity imitation of an atypical biological model presented in a randomized trial order in autism was suggested to occur due to disrupted sensorimotor control processes associated with the comparison of expected and actual sensorimotor consequences during, and between, imitation trials (Elliott et al. 2001; Wolpert et al. 2011). In the context of our model, this would impact both online impulse control and the generation of a new internal model for a subsequent trial. Importantly, by manipulating a learning environment so that the to-be-imitated model stimuli is presented in a predictable blocked trial order, we facilitated sensorimotor integration leading to significant improvements in the imitation of biological kinematics (Foster et al. 2020a). The fact that we facilitated imitation of atypical biological kinematics adds to the developing literature (Hamilton 2013; Sowden et al. 2016) that suggests imitation differences in autism are associated with general sensorimotor control processes, rather than specific processes related to action-observation

(Williams et al. 2001). These data, along with those where we showed autistic individuals significantly reduced spatial variability at peak acceleration and peak velocity (Foster et al. 2020b) during motor learning, indicate the underlying autistic sensorimotor control processes are responsive to training, whereby feedforward and feedback control processes are engaged specifically to develop novel internal action models (Gidley Larson et al. 2008; Hayes et al. 2018; Marko et al. 2015).

In summary, based on our multiple process model of goal-directed aiming, it appears that autistic individuals have difficulty producing and modulating the initial muscular forces required to move the limb toward the target (Foster et al. 2020b; Glazebrook et al. 2006). Consequently, this initial planning behavior influences down-stream visuomotor processing associated with limb control (Forti et al. 2011; Foster et al. 2020b; Rinehart et al. 2006) and prospective sensorimotor control (Whyatt and Craig, 2013). We originally suggested (Glazebrook et al. 2006) that autistic individuals adopted a strategy of moving more slowly in order to temper the increase in force variability associated with faster movements (Schmidt et al., 1979). Force production variability, and thus spatial variability, are typically associated with motor systems in which there is greater neural noise (Meyer et al., 1982; Schmidt et al., 1979). The idea that autistic individuals are required to accommodate a noisier perceptual-motor system has been suggested to relate to differences in everyday motor tasks, such as, handwriting and gait (Gowen and Hamilton 2013; Grace et al. 2018). Of critical importance is the fact that autistic individuals compensate for these sensorimotor planning differences by slowing down and taking more time to use response-produced feedback (Mosconi et al. 2015), and that the underlying processes associated with our multiple process model of limb control are ameliorated via training and practice leading to more efficient feedforward and feedback control (Foster et al. 2020b). Future investigations might extend our work on sensorimotor learning with autism by focusing on the relative contribution of impulse control and limb-target control in this regulatory process, and how practice variables (e.g., contextual interference; dyadic learning; knowledge of results feedback) in the learning environment can best facilitate motor adaptation.

Tetraplegia with Tendon Transfer Surgery

Over the last several years, members of our research group have had the opportunity to work with young men who have incurred partial paralysis of their upper limbs due to a C6 spinal cord injury (Robinson et al. 2010). A lesion at this level may leave the biceps brachii function intact but cause paralysis of triceps brachii. People with this type of injury can typically flex, but not extend their arm at the elbow joint. They can continue to make reasonably accurate reaching movements (Koshland et al. 2005; Mateo et al. 2015), and can appropriately scale their initial movement impulse to specific target distances (Laffont et al. 2000; Wierzbicka et al. 1992) as per healthy control individuals. However, their movement times are longer (Wiezbicka et al. 1992) with lower peak velocities (Koshland et al. 2005; Laffont et al. 2000). Because of

their inability to extend the arm at the elbow (i.e., triceps normal agonist) and decelerate elbow flexion (triceps normal antagonist), they depend on the shoulder musculature for reaching movements in all directions (Koshland et al. 2005).

In order to deal with the elbow flexion/extension issue associated with tetraplegia, some individuals undergo musculotendinous transfer surgery in which the posterior deltoid is inserted at the elbow to replace the triceps as the primary elbow extensor. This sub-set of individuals present a rather interesting population for discovering more about movement planning and limb control as existing perceptual-motor representations of upper limb movement at the posterior deltoid need to be adapted to incorporate information pertaining to the elbow. Several of these individuals agreed to participate in aiming experiments conducted by our research group (Robinson et al. 2010, 2014).

In our first study, we examined goal-directed aiming with elbow flexion and extension movements under conditions with full visual feedback and under conditions in which liquid crystal goggles eliminated vision of the arm and the target upon movement initiation (Robinson et al. 2010). Our participants with tetraplegia exhibited longer movement time and lower peak velocities than age equivalent control participants.[6] However, there were no differences in the symmetry of the movement trajectories. Moreover, they were equally accurate compared to control participants under both vision and no vision conditions. Interestingly, while the shapes of the limb trajectories were similar under both vision and no vision conditions, participants who had tendon transfer surgery required more absolute time to reduce spatial variability in the trajectory when elbow extension movements were required to complete the aiming movement. Of course, these were movements in which the transferred posterior deltoid muscle was the prime mover (i.e., agonist muscle). Like people with autism, it appears that individuals who have undergone tendon transfer surgery adopt a strategy of slowing down to compensate for greater force and spatial variability (i.e., a noisier force production system). Surprising to us was the degree of similarity in the spatial-temporal characteristics of the aiming movements (i.e., between the two groups, between vision condition, and between direction). Certainly, the sensorimotor system appears to be extremely adaptable. Moreover, these initial findings are consistent with the idea that the representations associated with precise control on aiming/reaching are not muscle specific (e.g., Marteniuk et al. 2000).

In follow-up work, we decided to take a more in-depth look at the structure of the aiming movements of this group (Robinson et al. 2014). Specifically, we parsed each aiming movement in order to identify discontinuities in velocity, acceleration, and jerk. These parsing protocols indicated that corrective submovements were no more evident in tendon-transfer participants than control participants. Movement reversals (i.e., negative velocity discontinuities) were almost completely absent in both groups. Thus, when a secondary submovement occurred, it was typically to correct a target undershoot. The longer movement times in people who had undergone tendon transfer surgery were also associated with

lower peak velocities and greater spatial variability at peak velocity. This indicates that these participants may have slowed their primary movement to accommodate a noisier neural-muscular system. When corrective submovements occurred, they were of a longer duration and larger amplitude in tendon-transfer participants. Presumably, this extra time and distance was required to manage the greater variability at peak velocity. In this context, people who had undergone tendon-transfer exhibited endpoint accuracy similar to control participants. Once again, we have evidence to indicate that people with a noisier and more variable primary movement make adjustments to their aiming behavior in order to achieve acceptable movement accuracy. In this case, they slow their primary movement to reduce impulse variability (and associated spatial variability), and also take more time for limb-target control late in the movement.

Summary and Conclusions

In this paper, we have used our multiple process model of goal-directed aiming/reaching as a framework for examining atypical limb control behaviors in several special populations. Our decision to consider typical aging, Down syndrome, autism spectrum disorder, and tetraplegia with tendon transfer surgery was based solely on the expertise and research history of the scientists in our group. An important feature of our model is that typical adult performers adopt strategic approaches to aiming and reaching that optimize not only movement speed and movement accuracy (e.g., Fitts 1954), but also energy expenditure (Elliott et al. 2009). Here, we show that participants from the four special populations also exhibit strategic approaches to the aiming/reaching task that minimize the impact of the additional constraints associated with their specific abilities and disabilities.

With respect to aging, where there is a general deterioration in multiple perceptual-motor systems, participants adopted a strategy of slowing down and undershooting the target with the initial movement impulse in order to avoid the temporal and energy costs associated with target overshooting. This strategic approach resulted in a greater reliance on limb-target control late in the movement for target acquisition. People with Down syndrome also perform aiming and reaching movements more slowly compared to adults without Down syndrome. However, in this case, it is likely because they have difficulty forming stable internal models that contribute to the feedforward component of early impulse control. Rather than exhibiting strategic target undershooting (cf. older adults), the limb trajectories of adults with Down syndrome are characterized by lower peaks and multiple discontinuities in the kinematics, which manifest particularly near the end of the movement (i.e., demonstrating a greater dependence on inefficient proprioceptive and visual limb-target control for people with Down syndrome).

Autistic adults also learn to slow down their movements in order to achieve acceptable movement accuracy while minimizing energy expenditure. This strategy is adopted to accommodate a noisier than average force production system

which results in greater spatial variability in the movement trajectory early in the movement. Part of this variability appears to stem for difficulties with sensorimotor integration that makes it more difficult for people with autism to develop an internal model of limb control for specific task demands. With respect to our model, this shortcoming associated with movement planning increases the probability of a mismatch between the perceived and expected sensory consequences of a particular aiming/reaching movement and thus impulse-control. To the advantage of autistic individuals however, this rapid feedback system appears to be operational and trajectory variability diminishes before the end of the primary movement. Importantly, this early feedforward process becomes more efficient and effective following sensorimotor training.

With respect to tetraplegia and tendon transfer, we have a group with presumably intact movement planning and visual feedback processing systems who now must execute elbow extension movements with a muscle that was not designed for that task. This same muscle (i.e., posterior deltoid) must also decelerate elbow flexion movements. This situation results in a noisier force production system that the performer accommodates by decreasing the absolute forces in goal-directed aiming and reaching movement in order to minimize spatial variability and thus increase movement accuracy. As our model specifies for typical adult performers, people with tendon transfer surgery must strike an optimal compromise between moving too quickly and producing movements that, on a large proportion of trials, require time and energy consuming corrective submovements, or moving so slowly that movement completion times are disproportionately long. Perhaps this is why the spatial-temporal characteristics of the aiming trajectories of people in this group most resembled those of control participants.

Almost 25 years ago, Latash and Anson (1996) wrote an important Brain and Behavioral Sciences commentary on "What are 'normal' movements in atypical populations?" They made the argument that when we study motor control and learning in atypical groups what we often see in their behaviors is adaptive attempts to minimize the impact of a compromised perceptual-motor system, rather than the perceptual-motor problem per se. As an example, the shuffling gait associated with Parkinson's disease probably reflects a strategy to minimize difficulties with balance and locomotion rather than a characteristic of the disease. Although we agree with this analysis at the movement outcome level, if one is guided by a theoretical model of motor control, and does a microanalysis of movement substructure in a variety of experimental contexts, it is sometimes possible to identify the problems as well as the adaptive solution developed by the specific atypical group. With the help of our model and detailed kinematic analyses, we believe have accomplished at least some of that goal here. Specifically, one consistent theme across the four groups we examined was the ability of the performers to adapt their movement strategy to accommodate, or at least limit the impact of, the constraints associated with their motor performance systems. Also apparent was the rather large impact even small changes to the environment and/or task demands had on some

types of performance. This latter finding provides promise to educators and health professionals tasked with helping people from various special groups optimize the goal-directed movements associated with daily living.

Acknowledgements

References

Anson JG, Mawston GA (2000) Patterns of muscle activation in simple reaction-time tasks. In: Weeks DJ, Chua R, Elliott D (ed) Perceptual-motor behavior in Down syndrome. Human Kinetics, Champaign Il., pp. 3-24

Ansuini C, Podda J, Battaglia FM, Veneselli E, Becchio C (2018) One hand, two hands, two people: Prospective sensorimotor control in children with autism. Dev Cog Neuro 29: 86-96

Augustyn JS, Rosenbaum DA (2005) Metacognitive control of action: Preparation of aiming reflects knowledge of Fitts's law. Psychonomic Bull Rev 12: 911-916

Bennett SJ, Elliott D, Rodacki A (2012). Movement strategies in vertical aiming in older adults. Exp Brain Res 216: 445-455

Bernstein NA (1967) The co-ordination and regulation of movements. Pergamon Press, Oxford

Burkitt JJ, Bongers RM, Elliott D, Hansen S, Lyons- JL (2017) Extending energy optimization in goal-directed aiming from movement kinematics to joint angles. J Motor Behav 49: 129-140

Burkitt JJ, Grierson LEM, Staite V, Elliott D, Lyons JL (2013) The impact of prior knowledge about visual feedback on motor performance and learning. Adv Phys Educ 3: 1-9

Burkitt JJ, Staite V, Yeung A, Elliott D, Lyons JL (2015) Effector mass and trajectory optimization in the online regulation of goal-directed movement. Exp Brain Res 233: 1097

Campione GC, Piazza C, Villa L, Molteni M (2016) Three-dimensional kinematic analysis of prehension movements in young children with autism spectrum disorder: New insights on motor impairment. J Autism Dev Disord 46: 1985-1999

Carson RG, Goodman D, Elliott D (1992) Asymmetries in the discrete and pseudo continuous regulation of visually guided reaching. Brain Cogn 18: 169-191

Chen H, Yeh C, Howe T (2015) Postural control during standing reach in children with Down syndrome. Res Dev Disabil 38: 345-351

Chen LC, Su WC, Ho TL, Lu L, Tsai WC, Chiu, YN., Jeng SF (2019) Postural control and interceptive skills in children with autism spectrum disorder. Phys Ther 99: 231-1241

Cook JD (2016) From movement kinematics to social cognition: the case of autism. Philos Trans R Soc B 371: 20150372

Cooke JD, Brown SH, Cunningham DA (1989) Kinematics of arm movements in elderly humans. Neurobiol Aging 10: 159-165

Cook JL, Blakemore SJ, Press C (2013) Atypical basic movement kinematics in autism spectrum conditions. Brain 136: 2816-2824

Darling WG, Cooke JD, Brown SH (1989) Control of simple arm movements in elderly humans. Neurobiol Aging 10: 149-157

Dawson G, Toth K (2006). Autism spectrum disorder. In: Cicchetti D, Cohen D. (eds.) Developmental psychopathology, Vol 3, 2nd ed Wiley, New York, pp. 317-257

Dounskaia NV, Ketcham CJ, Stelmach GE (2002) Commonalities and differences in control of various drawing movements. Exp Brain Res 146:11–25

Dowd AM, McGinley, JL, Taffe JR, Rinehart NJ (2012) Do planning and visual integration difficulties underpin motor dysfunction in autism? A kinematic study of young children with autism. J Autism Dev Disord 42: 1539-1548

Elliott D, Binsted G, Heath M (1999) The control of goal-directed limb movements: Correcting errors in the trajectory. Hum Mov Sci 18: 121-136

Elliott D, Carson RG, Goodman D, Chua R (1991) Discrete vs. continuous visual control of manual aiming. Hum Move Sci 10: 393-418

Elliott D, Dutoy C, Andrew M, Burkitt JJ, Grierson LEM, Lyons JL, Hayes SJ, Bennett SJ (2014) The influence of visual feedback and prior knowledge about feedback on vertical aiming strategies. J Motor Behav 46: 433-443

Elliott D, Hansen S (2010) Visual regulation of manual aiming: A comparison of methods. Behav Res Methods 42: 1087-1095

Elliott D, Hansen S, Grierson LEM (2009) Optimising speed and energy expenditure in accurate visually directed upper limb movements. Ergonomics 52: 439-447

Elliott D, Hansen S, Grierson LEM, Lyons JL, Bennett SJ, Hayes SJ (2010) Goal-directed aiming: two components but multiple processes. Psychol Bull 136: 1023-1044

Elliott D, Hansen S, Mendoza JE, Tremblay L (2004) Learning to optimize speed, accuracy, and energy expenditure: A framework for understanding speed-accuracy relations in goal-directed aiming. J Motor Behav 36: 339-351

Elliott D, Helsen WF, Chua R (2001) A century later: Woodworth's two-component model of goal directed aiming. Psychol Bull 127: 342-357

Elliott D, Lyons JL, Hayes SJ, Burkitt JJ, Roberts JW, Grierson LEM, Hansen S, Bennett SJ (2017) The multiple process model of goal-directed reaching revisited. Neurosci Biobehav Rev 72: 95-110

Elliott D, Welsh TN, Lyons JL, Hansen S, Wu M (2006) The visual regulation of goal-directed reaching in adults with Williams syndrome, Down syndrome, and other developmental delays. Mot Control 10: 34-54

Engelbrecht SE, Berthier NE, O'Sullivan LP (2003) The undershooting bias: Learning to act optimally under uncertainty. Psychol Sci 14: 257-261

Fitts PM (1954) The information capacity of the human motor system in controlling the amplitude of movement. J Exp Psychol 47: 381-391

Forti S, Valli A, Perego P, Nobile M, Crippa A, Molteni M (2011) Motor planning and control in autism. A kinematic analysis of preschool children. Res Autism Spect Dis 5: 834-842

Foster NC, Bennett SJ, Causer J, Elliott D, Bird G, Hayes SJ (2020a) Facilitating sensorimotor integration via blocked practice underpins imitation learning of atypical biological kinematics in autism spectrum disorder. Autism 24: 1494–1505

Foster NC, Bennett SJ, Causer J, Elliott D, Bird G, Hayes SJ (2020b) Getting off to a shaky start: Specificity in planning and feedforward control during sensorimotor learning in autism spectrum disorder. Autism Res 13: 423-435

Foti F, Menghini D, Alfieri P, Costanzo F, Mandolesi L, Petrosini L, Vicari S (2018) Learning by observation and learning by doing in Down and Williams syndromes. Dev Sci 21: e12642

Floris DL, Barber AD, Nebel MB, Martinelli M, Lai MC, Crocetti D, Baron-Cohen S, Suckling J, Pekar JJ, Mostofsky SH (2016) Atypical lateralization of motor circuit functional connectivity in children with autism is associated with motor deficits. Mol Autism 7: 35

Galganski ME, Fuglevand AJ, Enoka R. (1993) Reduced control of motor output in human hand muscle of elderly subjects during submaximal contractions. J Neurophysiol 69: 2108-2115

Ganglmayer K, Schuwerk T, Sodian B, Paulus M (2020) Do children and adults with autism spectrum condition anticipate others' actions as goal-directed? A predictive coding perspective. J Autism Dev Dis 50: 2077-2089

Gidley Larson JC, Bastian AJ, Donchin O, Shadmehr R, Mostofsky S H (2008) Acquisition of internal models of motor tasks in children with autism. Brain 131: 2894-2903

Gimenez R, Marquezi ML, Filho EX, Manoel ED (2017) A note on motor skill acquisition in mild and moderate Down syndrome individuals. Psicologia: Reflexão E Crítica: 30(1)

Glazebrook CM, Elliott D, Lyons J (2006) A kinematic analysis of how young adults with and without autism plan and control goal-directed movements. Mot Control 10: 244-264.

Glazebrook CM, Elliott D, Lyons J (2008). Temporal judgements of internal and external events in people with and without autism. Conscious Cogn 17: 203-209

Glazebrook CM, Elliott D, Szatmari P (2008) How do individuals with autism plan their movements? J Autism Dev Disord 38: 114-126

Glazebrook CM, Gonzalez D, Hansen S, Elliott D (2009) The role of vision for online control of manual aiming movements in people with autism spectrum disorder. Autism, 13: 411-433

Goggin NL, Stelmach GE (1990) Age-related differences in a kinematic analysis of precued movements. Can J Aging 9: 371-385

Gowen E, Hamilton A (2013) Motor abilities in autism: a review using a computational context. J Autism Dev Disord 43: 323-344

Grace N, Johnson BP, Rinehart NJ, Enticott PG (2018) Are motor control and regulation problems part of the ASD motor profile? A handwriting study. Dev Neuropsychol 4*3*: 581-594

Grierson LEM, Elliott D. (2009a) Goal-directed aiming and the relative contribution of two online control processes. Am J Psychol 122: 309-324

Grierson LEM, Elliott D (2009b) The impact of real and illusory target perturbations on manual aiming. Exp Brain Res 193: 279-285

Hamilton, AFDC (2013) Reflecting on the mirror neuron system in autism: a systematic review of current theories. Dev Cog Neuro 3: 91-105

Hansen S, Glazebrook CM, Anson JG, Weeks DJ, Elliott D (2006) The influence of advance information about target location and visual feedback on movement planning and execution. Can J Exp Psychol 60: 200-208

Hansen S, Sheahan B, Wu M, Lyons JL, Welsh TN, Elliott D (2005) Specificity of learning in adults with and without Down syndrome. Adapt Phys Activ Q 22: 237-252

Haswell CC, Izawa J, Dowell LR, Mostofsky SH, Shadmehr R (2009) Representation of internal models of action in the autistic brain. Nat Neurosci 12: 970-972

Hayes SJ, Andrew M, Elliott D, Gowen E, Bennett SJ (2016) Low fidelity imitation of atypical biological kinematics in autism spectrum disorder is modulated by self-generated selective attention. J Autism Dev Disord 46: 502-513

Hayes SJ, Andrew M, Foster NC, Elliott D, Gowen E, Bennett SJ (2018) Sensorimotor learning and associated visual perception are intact but unrelated in autism spectrum disorder. Autism Res 11, 296-304

Heath M (2005) Role of limb and target vision in the online control of memory-guided reaches. Mot Control 9: 281-309

Heath M, Hodges NJ, Chua R, Elliott D (1998) On-line control of rapid aiming movements: Unexpected target perturbations and movement kinematics. Can J Exp Psychol 52: 163-173

Helsen WF, Elliott D, Starkes JL, Ricker KL (1998) Temporal and spatial coupling of point of gaze and hand movements in aiming. J Motor Behav 30: 249-259

Helsen WF, Van Halewych F, Levin O, Boisgontier MP, Lavrysen A, Elliott D (2016) Manual aiming in healthy aging: does proprioceptive acuity make the difference? Age 38: 45

Hill EL (2004). Executive dysfunction in autism Trends Cogn Sci 8: 26-32

Hocking D, Rinehart N, Mcginley J, Galna B, Moss S, Bradshaw J (2011) Gait adaptation during obstacle crossing reveals impairments in the visual control of locomotion in Williams syndrome. Neurosci 197: 320-329

Hodges NJ, Cunningham SJ, Lyons JL, Kerr TL, Elliott D (1995) Visual feedback processing and goal-directed movement in adults with Down syndrome. Adapt Phys Activ Q 12: 176-186

Hoffmann G, Laffont I, Hanneton S, Roby-Brami A (2006) How to extend the elbow with a weak or paralyzed triceps: control of arm kinematics for aiming in C6-C7 quadriplegic patients. Neurosci 139: 749-765

Hughes C (1996) Brief report: Planning problems in autism at the level of motor control. J Autism Dev Disord 26: 99-106

Keele SW (1968) Movement control in skilled motor performance. Psychol Bull 70: 387-403

Kelso JAS (2012) Multistability and metastability: understanding dynamic coordination. Philos Trans R Soc B Biol Sci 367: 906-918

Kenny L, Hattersley C, Molins B, Buckley C, Povey C, Pellicano E (2016) Which terms should be used to describe autism? Perspectives from the UK autism community. Autism 20, 442-462

Kerr R, Blais C (1985) Motor skill acquisition by individuals with Down syndrome. Am J Ment Def 90(3): 313-318

Ketcham CJ, Seidler RD, van Gemmert AWA, Stelmach GE (2002) Age-related kinematic differences as influenced by task difficulty, target size and movement amplitude. J Gerontol: Psychol Sci 57B: P54-P64

Khan MA, Elliott D, Coull J, Chua R, Lyons JL (2002) Optimal control strategies under different feedback schedules: Kinematic evidence. J Motor Behav 34: 45-57

Kitchen NM, Miall RC (2019) Proprioceptive deficits in inactive older adults are not reflected in fast targeted reaching movements. Exp Brain Res 237: 531-545

Koshland GF, Galloway JC, Farley B (2005) Novel muscle patterns for reaching after cervical spinal cord injury: a case for motor redundancy. Exp Brain Res 164: 133-147

Lam MY, Hodges NJ, Virji-Babul N, Latash ML (2009) Evidence for slowing as a function of index of difficulty in young adults with Down syndrome. Am J Intellect Dev Disabil 114: 411-426

Latash ML, Anson JG (1996) What are 'normal movements' in atypical populations? Behav Brain Sci 19: 55-68

Lawrence GP, Reilly NE, Mottram TM., Khan MA, Elliott D (2013). Sequential aiming movements and the one-target advantage in individuals with Down syndrome. Res Dev Disabil 34: 3858-3866

LeClair DA, Pollock BJ, Elliott D (1993). Movement preparation in adults with and without Down syndrome. Am J Ment Retard 97: 628-633

Lopes JB, Duarte ND, Lazzari RD, Oliveira CS (2018) Virtual reality in the rehabilitation process for individuals with cerebral palsy and Down syndrome: A systematic review. J Bodyw Mov Ther

Lord C, Brugha TS, Charman T, Cusack J, Dumas G, Frazier T, Jones EJ, Jones RM, Pickles A, State MW, Taylor JL (2020) Autism Spectrum Disorder. Nat Rev Dis Primers 6: 1-23

Lyons J, Elliott D, Swanson LR, Chua R (1996) The use of vision in manual aiming by young and older adults. J Aging Phys Act 4: 165-178

Lyons J, Hansen S, Hurding S, Elliott D (2006) Optimizing rapid aiming behaviour: Movement kinematics depend on the cost of corrective modifications. Exp Brain Res 174: 95-100

Mari M, Castiello U, Marks D, Marraffa C, Prior M (2003) The reach-to-grasp movement in children with autism spectrum disorder. Philos Trans R Soc Lond B. Biol Sci 358: 393-403

Marko, MK, Crocetti D, Hulst T, Donchin O, Shadmehr R, Mostofsky SH (2015) Behavioural and neural basis of anomalous motor learning in children with autism. Brain 138: 784-797

Marteniuk RG, Ivens CJ, Bertram CP (2000) Evidence of motor equivalence in a pointing task involving locomotion. Mot Control 4: 165-184

Mateo S, Roby-Brami A, Reilly KT, Rossetti Y, Collet C, Rode G (2015) Upper limb kinematics after cervical spinal cord injury: a review. J Neuroeng Rehabil 12: 9

Mendoza JE, Elliott D, Meegan DV, Lyons JL, Welsh TN (2006) The effect of the Müller-Lyer illusion on the planning and control of manual aiming movements. J Exp Psychol: Hum Percept Perform 32: 413-422

Meyer DE, Abrams RA, Kornblum S, Wright CE, Smith JEK (1988) Optimality in human motor performance: Ideal control of rapid aimed movements. Psychol Rev 95: 340-370

Monteiro CB, Silva TD, Abreu LC, Fregni F, Araujo LV, Ferreira FH, Leone C (2017) Short-term motor learning through non-immersive virtual reality task in individuals with Down syndrome. BMC Neurol 17(1)

Mon-Williams M, Tresilian JR, Bell VE, Coppard VL, Jobling A, Carson RG (2001) The preparation of reach to grasp movements in adults with Down syndrome. Hum Move Sci 20: 587-602

Mosconi MW, Mohanty S, Greene RK, Cook EH, Vaillancourt DE, Sweeney JA (2015) Feedforward and feedback motor control abnormalities implicate cerebellar dysfunction in autism spectrum disorder. J Neurosci 35: 2015-2025

Mostofsky SH, Ewen JB (2011). Altered connectivity and action model formation in autism is autism Neuroscientist 17: 437-448

Nazarali N, Glazebrook CM, Elliott D (2009) Movement planning and reprogramming in individuals with autism. J Autism Dev Disord 39: 1401-1411

Obhi SS, Lyons J, Welsh TN, Glazebrook CM, Anson G, Elliott D (2007) The perceived time of voluntary action for adults with and without Down syndrome. Down Syndrome Q 9: 4-9

Oliveira FTP, Elliott D, Goodman D (2005) The energy minimization bias: Compensating for intrinsic influence of energy minimization mechanisms. Mot Control 9: 101-114

Papadopoulos N, McGinley J, Tonge BJ, Bradshaw JL, Saunders K, Rinehart NJ (2012) An investigation of upper limb motor function in high functioning autism and Asperger's disorder using a repetitive Fitts' aiming task. Res Autism Spect Dis 6: 286-292

Park J-H, Shea CH (2003) Effect of practice on effector independence. J Motor Behav 35:33–40

Pillai AS, McAuliffe D, Lakshmanan BM, Mostofsky SH, Crone NE, Ewen JB (2018) Altered task-related modulation of long-range connectivity in children with autism. Autism Res 11: 245-257

Pitetti K, Baynard T, Agiovlasitis S (2013) Children and adolescents with Down syndrome, physical fitness and physical activity. J Sport Health Sci 2(1): 47-57

Poletti C, Sleiman-Malkoun R, Decker LM, Refornaz F, Lemaire P Temprado J-J (2017) Strategic variations in Fitts' task: Comparison of healthy older adults and cognitively impaired patients. Front Aging Neurosci 8: 334

Poletti C, Sleimen-Malkoun R, Lemaire P, Temprado J-J (2016) Sensori-motor strategic variations and sequential effects in young and older adults performing Fitts' task. Acta Psychol 163: 1-9

Poletti C, Sleimen-Malkoun R, Temprado J-J, Lemaire P (2015) Older and younger adults' strategies in sensori-motor tasks: insights from Fitts' pointing task. J Exp Psychol: Hum Percept Perform 41: 542-555

Possebom F, Massetti T, da Silva T, Malheiros S, Menezes L, Caromano F, Ré A, Bezerra I, Monteiro C (2016) Maze computer performance in Down syndrome. J Hum Growth Dev 26 (2): 205-210

Pratt J, Chasteen AL, Abrams RA (1994) Rapid aimed movements: Age differences and practice effects in component submovements. Psychol Aging 9: 325-334

Prinz W (1997) Perception and action planning Eur J Cogn Psychol 9 (2): 129-154

Puts NA, Wodka EL, Harris AD, Crocetti D, Tommerdahl M, Mostofsky SH, Edden RA (2017) Reduced GABA and altered somatosensory function in children with autism spectrum disorder. Autism Res 10: 608-619

Reilly N, Lawrence GP, Mottram T, Khan M (2017) Adults with Down syndrome demonstrate peripheral, not central, deficits when integrating movements during multiple-target sequences. J Mot Learn Dev 5:82-102

Rinehart NJ, Bellgrove MA, Tonge BJ, Brereton AV, Howells-Rankin D, Bradshaw JL (2006) An examination of movement kinematics in young people with high-functioning autism and Asperger's disorder: Further evidence for a motor planning deficit. J Autism Dev Disord 36: 757-767

Roberts JW (2020) Energy minimization within target-directed aiming: the mediating influence of the number of movements and target size. Exp Brain Res 238: 741-749.

Roberts JW, Grierson LEM (2019) Early impulse control: treatment of potential errors within pre-programming and control. J Mot Behav

Roberts JW, Wilson MR, Skultety JK, Lyons JL (2018) Examining the effect of state anxiety on compensatory and strategic adjustments in the planning of goal-directed aiming. Acta Psychol 185: 33-40

Robinson MA, Elliott D, Hayes SJ, Barton GJ, Bennett SJ (2014) Primary and submovement control in C6 tetraplegics following posterior deltoid transfer. J NeuroEng Rehabil 11: 1-9

Robinson MA, Hayes SJ, Bennett SJ, Barton GJ, Elliott D. (2010). Sensory-motor equivalence: manual aiming in C6 tetraplegics following musculotendinous transfer surgery at the elbow. Exp Brain Res 206: 81-91

Salthouse TA (2009). When does age-related cognitive decline begin? Neurobiol Aging 30: 507-514

Schmidt RA (1975) A schema theory of discrete motor skill learning. Psychol Rev 82: 225–260

Schmidt RA, Zelaznik HN, Hawkins B, Frank JS, Quinn JT (1979) Motor output variability: A theory for the accuracy of rapid motor acts. Psychol Rev 86: 415-451

Sleiman-Malkoun R, Temprado J-J, Berton E (2013) Age-related changes of movement patterns in discrete Fitts' task. BMC Neurosci 14: 145

Slifkin AB, Eder JR (2017) Degree of target utilization influences the location of movement endpoint distributions. Acta Psychol 174: 89-100

Smith BA, Kubo M, Black DP, Holt KG, Ulrich BD (2007) Effect of practice on a novel task-walking on a treadmill: preadolescents with and without Down syndrome. Phys Ther 87: 766-777

Sosnoff JJ, Newell KM (2006) Aging, visual intermittency and variability in isometric force output. J Gerontol B-Psychol 61: P117-124

Sowden S, Koehne S, Catmur C, Dziobek I, Bird G (2016) Intact automatic imitation and typical spatial compatibility in autism spectrum disorder: Challenging the broken mirror theory. Autism Res 9: 292-300

Stewart HJ, McIntosh RD, Williams JHG (2013) A specific deficit of imitation in autism spectrum disorder. Autism Res 6 (6): 522-530

Stoit AB, van Schie H, Slaats-Willemse DE, Buitelaar J (2013) Grasping motor impairments in autism: Not action planning but movement execution is deficient. J Autism Dev Disord 43: 2793-2806

Swinnen SP, Vangheluwe S, Wagemans J, Coxon JP, Goble DJ, Van Impe A, Sunaert S, Peeters R, Wenderoth N (2010) Shared neural resources between left and right inter limb coordination skills: the neural substrate of abstract motor representations. NeuroImage 49:2570–2580

Szatmari P, Tuff L, Finlayson MA, Bartolucci G (1990) Asperger's syndrome and autism: Neurocognitive aspects. J Am Acad Child Adolesc Psychiatry 29: 130-136

Temprado J-J, Sleiman-Malkoun R, Lemaire P, Rey-Robert B, Retornaz F, Berton E (2013) Aging of sensorimotor processes: a systematic study in Fitts' task. Exp Brain Res 228: 105-116

Temprado J-J, Vieluf S, Sleiman-Malkoun R (2017) Age-related changes in force control under different task contexts. Exp Brain Res 235: 231-246

Valvano J, Hogy S, Worster K, Ma J, Denniston N, Winders P Carollo JJ (2017) Analysis of reach-to-grasp by school-aged children with Down syndrome elucidates limitations in upper extremity motor control. Phys Occup Ther Pediatr 37(4): 374-388

Vaillancourt JJ, Newell KM (2003) Aging and the time and frequency structure of force output variability. J Appl Physiol 94: 903-912

Van Halewyck F, Lavrysen A, Levin O, Boisgontier MP, Elliott D, Helsen, WF (2014) Both age and physical activity level impact on eye-hand coordination. Hum Move Sci 36: 80-96

Van Halewyck F, Lavrysen A, Levin O, Elliott D, Helsen WF (2015) The impact of age and physical activity level on manual aiming performance. J Aging Phys Act 23: 169-179

Vimercati SL, Galli M. Rigoldi C, Albertini G (2013a) Obstacle avoidance in Down syndrome J Electromyogra Kines 23: 483-489

Vimercati SL, Galli M, Rigoldi C, Ancillao A, Albertini G (2013a) Motor strategies and motor programs during an arm tapping task in adults with Down syndrome. Exp Brain Res 225(3): 333-338

Vimercati SL, Galli M, Rigoldi C, Ancillao A, Albertini G (2013b) Feedback reliance during an arm-tapping task with obstacle avoidance in adults with Down syndrome. Exp Brain Res 226: 631-638

Vivanti G, Hamilton AFDC (2014) Imitation in autism spectrum disorders handbook of autism and pervasive developmental disorders 4th ed. Wiley, New Jersey

Welsh TN, Higgins L, Elliott D (2007) Are there age-related differences in learning to optimize speed, accuracy, and energy expenditure? Hum Move Sci 26: 892-912

Whyatt CP, Craig CM (2013) Interceptive skills in children aged 9–11 years, diagnosed with Autism Spectrum Disorder. Res Autism Spect Dis 7: 613-623

Wierzbicka MM, Wiegner AW (1992) Effects of weak antagonist on fast elbow flexion movements in man. Exp Brain Res 91: 509-519

Wild KS, Poliakoff E, Jerrison A, Gowen E (2012) Goal-directed and goal-less imitation in autism spectrum disorder. J Autism Dev Disord 42 (8): 1739-1749

Williams JH, Whiten A, Suddendorf T, Perrett, DI (2001) Imitation, mirror neurons and autism. Neurosci Biobehav Rev 25: 287-295

Wolpert DM, Diedrichsen J, Flanagan RJ (2011) Principles of sensorimotor learning. Nat Rev Neurosci 12: 739-751

Wolpert DM, Ghahramani Z (2000) Computational principles of movement neuroscience. Nat Neurosci 3: 1212-1217

Woodworth RS (1899) The accuracy of voluntary movement. Psychol Rev 3 Monograph Supplement: 1-119.

Worringham CJ (1991) Variability effects on the internal structure of rapid aiming movements. J Motor Behav 23: 75-85

Wu J, Ulrich DA, Looper J, Tiernan CW, Angulo-Barroso RM (2008) Strategy adoption and locomotor adjustments in obstacle clearance of newly walking toddlers with Down syndrome after different treadmill interventions. Exp Brain Res 186: 261-272

Wuang, Y, Chiang C, Su C, Wang C (2011) Effectiveness of virtual reality using Wii gaming technology in children with Down syndrome. Res Dev Disabil 32(1): 312-321

Zheng R, Naiman ID, Skultety J, Passmore SR, Lyons JL, Glazebrook CM (2019) The impact of different movement types on motor planning and execution in individuals with autism spectrum disorder. Mot Control, 23, 398-417.

Footnotes

1. In the majority of studies covered in this review, the term "older" refers to participants of 60 years plus while "younger" participants are typically under the age of 40 years.

2. Helsen and colleagues (2016; *cf.* Kitchen and Miall 2019) suggested that at least part of the conservative strategy adopted by older adults may be related to a deterioration in proprioceptive sensitivity. It is certainly possible that age-related deterioration in several sensory-motor systems contributes to the play-it-safe aiming strategy generally adopted by older adults.

3. Professional discourse around disability has typically adopted a person-centered approach, which aims to describe the individual as a person that has a disability rather than a person who is disabled. In recent years, however, there has been a push from within the autism community to alter the use of language so as to take a disability-first approach; that is, to describe autistic individuals rather than persons with autism (Kenny et al. 2016). The fundamental idea is that person-centered language implies that there is a 'typical' person that can be understood as separate from their autism, rather than a person whose life is in part defined by being autistic This position is consistent with the perspectives of the autistic individuals with whom we have worked, and we have accordingly adopted that terminology in this manuscript.

4. Unlike people with Down syndrome, autistic adults exhibit an anticipatory awareness of their own movements (Glazebrook et al. 2008). This ability along with efficient impulse control suggests adults with autism form and maintain at least some type of representation of impending action.

5. Mosconi and colleagues (2015) reported greater force variability in individuals with autism during an isometric force production task. Specifically, variability differences between individuals with and without autism increased with the absolute magnitude of the isometric target force and were more pronounced when visual feedback was disrupted.

6. This kinematic result was similar to the findings for outward aiming movements of tetraplegics without tendon transfer (e.g., Koshland et al. 2005). The difference of course was that the reaching movements in the Robinson et al. (2010, 2014) work involved the elbow and not the shoulder. In research involving tetraplegia, both with and without tendon transfer surgery, the control group has always been neurotypicals. To our knowledge, the two groups have not been compared to each other.