Bridging the Gap Between Mobility Perception and Performance for Aging Manual Wheelchair Users

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Industrial and Operations Engineering)
in the University of Michigan
2024

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Dedication

To my family, whom I love very much.

Acknowledgements

This accomplishment and incredible milestone are not only mine, but they also belong to everyone who supported and lifted me up along the way.

Thank you to my advisor, Dr. Chevalier Bernard J. Martin, for your acceptance of my ideas, guidance in refining said ideas towards proposals, rigorous research, and presentations. Your encouragement, trust and respect, and humor not only made these endeavors possible, but they also boosted my confidence as a researcher. Your keen insights and reassurance continue to push me to learn. I shall never forget the muscle length-tension curve.

Thank you to my committee. Dr. James Ashton-Miller, Dr. Michelle A. Meade, and Dr. Leia Stirling, for your support and patience as I formulated and refined my ideas. All of your feedback was constructive, and I never felt torn down—rather, I was always encouraged to rise to the challenge and meet the level of rigor expected. I learned so much from your shared expertise and guidance, from the Preliminary Exam (Dr. Ashton-Miller, you encouraged me to find my voice within the research, to show audiences my passion and highlight the value of inclusion), to striving to achieve equitable access for participants (Dr. Meade, you shared many insights and supported our fight, even when it seemed impossible), to initial presentations of results (Dr. Stirling, you guided me to see the value and broader impact of my work, and you encouraged me to take action while finding a healthy work-life balance).

Thank you to my master’s advisor who remained my mentor throughout these years, Dr. Kate Hunter-Zaworski. Your encouragement and motherly love, as we both always call it, helped me find confidence even in the face of doubt. Without you, I would not have found my love for human factors or inclusion work.

Thank you to my cohort, peers, and friends in IOE, COE, and COHSE—and the many others I have connected with during my time at U-M and beyond. You are all too numerous to name, but truly your friendships helped me to find the balance and joys in this “marathon”. This research could not have been accomplished without your support or the support of the C4E and IOE staff, all of whom I also consider my friends after all these long years of working together. To the research team in the Human Sensory-Motor and Vibrations Lab, Aaron Sun, Emily Nakisher, Ekim Koca, and Dr. Augustine Acquah; thank you for all of your hard work and brilliant ideas. The hours and effort you contributed to this research is greatly appreciated.

Thank you to my family who have supported me from Day 1, in life, not just in this PhD journey. My parents, Uthai and Watchara Tabattanon, who flew from Thailand to road trip me from Oregon to my dream school. From checking in to make sure I am eating and sleeping well (which I did not always do), to flying to visit me to provide much-needed TLC, and to always providing words of encouragement and pictures of Sushi to boost morale, your love and pride for me have given me my drive to succeed-- and not of small significance, Papaa wore a U-M t-shirt for me despite being an OSU alum. My younger sibling, Tasha, who technically was there starting Day 2,575 of life, your worldly adventures and shared posts and pictures have brought much joy. You and Mamee designed basically my entire wedding. I will continue to pay my dues and hopefully this PhD advances my ability to send you more stuffed animals and knick-knacks than you could ever want. I love you all, and this is as much your victory as it is mine.

Thank you to my loving husband Dom, who happily “dealt with” me day and night, from the snoozed alarms, stolen snacks (I eat your chips when you don’t notice), and late nights waking you up to tell you about my dissertation-related dreams; I could not have done this without you. Your care for me and the boys, Baby Sirloin and Nugget, has kept me healthily fed and with an acceptable amount of sleep each night. You moved from Texas to be here together as a family, and for that I am grateful. On top of that, your aura of fun and joy has drawn in so many friends, and my life is much richer for it. I love my honey. Thank you also to my best friends, the BAEs. Your humor, our check-ins and work-together sessions on FaceTime, our few yet very significant meet ups— all of these have a special place in my heart, and I thank you for your love.

Thank you to the research and funding supports: the NIOSH traineeship from COHSE and C4E, the Rackham Research and Travel Grants, and the NIOSH Pilot Project Research Training Grant. Dr. Martin, Dr. Stirling, and Dr. Sheryl Ulin, without your support and encouragement, I would not have achieved these successes. Thank you also to the national and U-M chapters of the Human Factors and Ergonomics Society. I have formed so many meaningful connections and friendships, it is difficult to imagine my life and future professional career without this group. I look forward to continuing to work with you all.

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Abstract

The population of aging adults is rapidly increasing worldwide. Inequity in mobility independence alongside increasing disability incidence during aging reduce quality of life and participation- which are critical as the desire and need to work into older age rises. Manual wheelchairs (MW) have become increasingly relied upon by aging adults to support mobility loss. Therefore, in order to support safe and equitable MW use within the aging population, there is a need to design effective and practical environment-based interventions that are applicable to a large range of manual wheelchair users (MWUs). This dissertation applied a novel integration of human factors engineering and motor control theories to improve mobility task-environments and the corresponding design/evaluation process to better include the needs of aging MWUs. In doing so, *MW incidence period* and *simulated impairment (SI)* were also distinguished to investigate the usefulness and validity, respectively, within research and design. Our findings show that interventions of *simple, augmented visuospatial information* within path-following environments successfully facilitated underlying somatoperception and somatorepresentation processes for MWUs. Specifically, the top-down intervention improved MWU ability to align their assumed frustration with their perceived frustration associated with a movement task (from 80% difference in Baseline to 29% with the intervention), which is necessary to promote confidence and reduce self-limited participation. Bottom-up interventions improved the congruency between participants' perception of performance and the objective measure of movement accuracy (e.g., collisions committed) was improved as high as 28% (percent increase;

resulting in correlation up to r = 0.88 among MWUs) by the BU interventions. in addition, MWUs with later-in-life incidence no longer committed more collisions than those with earlier-in-life incidence (LL: 1.22(1.81) collisions in the 6m straight line displacement; EL: 0.57 (0.12)) in the presence of both top-down (LL: 0.66(1.11); EL: 0.33(0.49)) and bottom-up interventions (LL: 0.44(0.89); EL: No collisions observed).

Further, this work revealed the invalidity/bias of using SI in both research and design endeavors, as the space required to perform a common maneuvering task was significantly less for the SI (7.0cm, CI^{95}: 0.8) than the MWUs (8.9cm, CI^{95}: 2.2). SI participants also commented on very different themes than the MWUs ("a fun experience" vs. "reminders of stressful situations faced in daily life", respectively), highlighting differences in somatorepresentations and relevant task stressors between the two groups. In sum, this dissertation showcased how concepts borrowed from motor control theory offers new and attractive perspectives for human factors and accessibility research. This work offers recommendations to design and assess inclusive environment-based, augmented visuospatial feedback interventions that effectively consider underlying sensorimotor processes and reveal simulation of impairment cannot be a surrogate to represent the reality of MWUs in research.

Chapter 1 Literature Review

The population and proportion of aging adults is rapidly increasing worldwide, with growth rates in populations 65 years and older greater than any other age group[1,2]. In the US, the combination of aging Baby Boomers and lower birthrates compared to the 1950s and 1960s has led to a "graying" population, or the "Gray Wave"[3,4].

Alongside this "graying" trend, aging adults in the US are also becoming more ethnically and racially diverse; working into older age; and experiencing increasing incidence of disability across all household incomes, race/ethnicities, and sexes[4–8]. Among the intersection of these trends are a number of relevant concerns:

> *Aging adults with disability are being left behind, adding to an urgent societal need*[9]. In 2022, nearly 80% of adults with disability were not in the workforce, and over half of those with disability who were employed were age 65 and above[10]. In comparison, the US essential workforce consists of 16.1 million workers aged 50 years and older (37.3% of the total workforce), and 6.4 million are age 60 years and older (14.7%)[11]. Yet 30% of workers with disability were employed part-time only, compared to 16% of counterparts without disability, with 4% being due to reduced hours[10]. Further, 44% of persons with disability seeking employment became discouraged due to reasons including discrimination from age and disability, a lack of training or access to training, or feeling work for them is unavailable[10]. Furthermore, the way people with disability physically move within employment contexts, including in terms of transportation and employment

access, has been investigated, and findings reveal that many aspects of mobility remain inequitably supported, resulting in inequality, reduced participation and quality of life, and negative psychosocial impact[12–14].

Who we recruit in research and human factors studies is important, however,…

…simulated impairment for disabilities is often without validation for the assumptions of representativeness compared to actual populations with disabilities. Simulated impairment (SI) is defined as the interactive role-playing experience applied to simulate capability loss or limitations[15]. SI is used, for example, with hopes to bring disability or aging "perspectives" to design or environmental evaluation[15–18]. The literature on SI focuses on empathy and emotional outcomes of participants who experience simulations, and findings highlight unintended consequences such as misattribution of challenges (i.e., "blaming" a health condition as the source of disability as opposed to inaccessible systems), formation of negative or harmful views of people with disabilities, and misplaced confidence that "all" pain points can be experienced through SI[15,18–20]. Concerningly, SI has not been validated in performance and design evaluation contexts. In fact, the first study, to the best of our and the paper's authors' knowledge, to examine the validity of suits used for simulating age-related limitations was published in September 2023[16]. Results were mixed, finding that 'accurate' simulation of age-related impairments depended on the age of the individual undergoing simulation and the task; and a failure to simulate more serious functional losses[16]. Hence, further validation is required for simulations of disability.

…within the general aging adult population, the rising later-in-life incidence of mobility disability creates a population that has not been well investigated. There has been an

increase in disability incidence within the current generation of aging adults compared to the same age group a decade prior[7]. Following the World Health Organization's (WHO's) International Classification of Functioning, Disability, and Health (ICF), one would expect this later-in-life (LL) disability incidence to result in people exhibiting different capabilities compared to peers with earlier-in-life (EL) disability incidence[21]. This issue must be considered since differing capabilities will yield differing inclusion needs even in similar task-environments[21,22]. Our society must strive to support individuals who age into mobility disability in employment, transportation, and daily needs to facilitate mobility and thus improve independence[23,24]. Yet what must be explored is: older adults with LL incidence of mobility disability may additionally face increasing injury risk and reduced performance and participation[25].

This dissertation investigates ways in which human factors and an understanding of motor action perception can address these challenges and improve task-environments for manual wheelchair users, inclusive to those with LL incidence of disability. This will be achieved via a focus on human sensorimotor functions and internal motor planning. This introductory chapter presents a literature review within the relevant interdisciplinary fields to address the following overarching hypotheses:

H1) Interventions to augment visuospatial information within the environment will support mobility performance for aging manual wheelchair users (MWUs).

- Specifically, *interventions* will facilitate navigation and wheelchair movement control.

H2) Mobility performance and influence of interventions will differ with incidence period (earlier-in-life vs later-in-life) within an aging MWU population.

- Specifically, those with later-in-life incidence of MW usage will benefit more from intervention support; for example, by the Ecological Model of Adaptation and Aging[26].

H3) While using a MW, mobility performance will differ between those who simulate impairment (i.e., do not use a wheelchair in real life situations) and MW users (i.e., are impacted by a mobility impairment).

-It is postulated that performance will be better for for the sis than the mwu despite their inexperience in mobility**.**

1.1 Aging adults with mobility disability

Mobility during later life is critical for healthy, independent, and successful aging[27,28]. Inadequate mobility independence in the face of disability reduces one's independence and quality of life, leading over 22% of older adults to be dependent on others with increasingly reliance on unpaid services (e.g., family)[29,30].

However, mobility has become discriminatory with inadequate accessibility within built environments, including places of work, and transportation[12,31]. Of concern, 42% of older adults in the US report disability, most prevalently related to mobility and with greater odds within Indigenous and African American populations[32,33]. In fact, mobility limitation is the most prevalent disability in the general US population[6,31,32]. Towards mobility support, ambulation or mobility aids are commonly used. Manual wheelchairs (MW) have become increasingly relied upon by aging adults to support mobility loss as access to wheelchairs improves and stigma decreases[34,35]. However, unsupported usage can be unsafe[36–38]. In 2003, older adults accounted for 69% of the wheelchair injury cases that impact 18% of users annually; 73% of these older adult injury cases resulted in contusion, laceration, or fracture[37,39]. Such injuries are not only acutely hazardous-- they may also result in long-term loss of independence, ability to work and participate, and lowered quality of life[38]. Yet, MW training is inequitable and not always available upon incidence of mobility limitation[40,41]. One study at a Canadian rehabilitation center found that only 55% of MW in-patients received MW training upon discharge[38,41]. Furthermore, as humans age, the ability to train new motor programs are reduced[42–44]. Hence, those at the intersection of age-related slowing and LL disability incidence of MW usage are at an elevated risk for injury and greater limitation of independent mobility.

1.1.1 Defining disability

Before we proceed, it is crucial to define disability and how it will be viewed in the following chapters. *Disability* is defined within this dissertation through the perspective of the International Classification for Functioning, Disability, and Health (ICF); that is, a disability is not solely expressed by a health condition (e.g., Bob has osteoarthritis.). Rather, disability arises from a combination of a person’s functional capability, contextual task-environment factors, and personal factors (e.g., Bob’s osteoarthritis reduces his capability to walk through the park because it lacks sidewalks and benches for him to rest; therefore, a disability arises, preventing him from taking his daily walk.)[45,46]. Figure 1.1 presents the ICF framework.

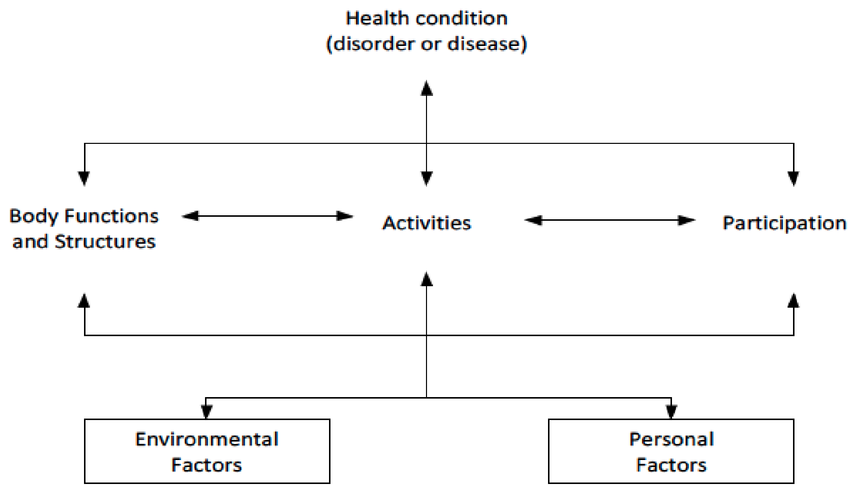


Figure 1.1: ICF framework diagram, reproduced from WHO (2013) [45].

1.1.2 Simulations of disability

Simulated impairment (SI) is defined as the interactive role-playing experience applied to simulate capability loss or limitations[15]. SI is used, for example, with hopes to bring disability or aging "perspectives" to healthcare training, empathy education, and design or environmental evaluation[15–18]. Examples of simulations include wearing restrictive gloves to mimic reduced joint range of motion and using a walker to increase one's spatial footprint (both, see Figure 1.2). While mixed results have been reported in education contexts for empathy, negative findings highlight the unintended consequences such as misattribution of challenges (i.e., "blaming" a health condition as the source of disability as opposed to inaccessible systems), formation of negative or harmful views of people with disabilities, or misplaced confidence that "all" pain points can be experienced through SI[15,18–20]. It can thus lead to the stereotyping of an "other" group as being less capable compared to a "normal, abled" group[20,47].

Figure 1.2: Example of simulated impairment. An age-simulation suit is shown, along with the simulated need for an ambulation aid (i.e., the walker) and a mobility aid (i.e., the manual wheelchair).

Of direct relevance to this project, SI has been used within early- and late-stage design evaluations of tasks, including for usability. The evaluations included performance, spatial and/or physiological measures[48–52]. Concerningly, SI has not been validated in the context in which it is used[48]. This sentiment was echoed at the 3th Annual Center for Disability Health and Wellness (CDHW) Symposium in October 2022[48]. A September 2023 article in the Journal of Experimental Aging Research from Gerhardy et al.[16] is, to the best of authors' and our knowledge, the first study to examine the validity of age simulation suits (i.e., specialized suits that are commercially available to simulate age-related impairments). In their experiment, Gerhardy et al. found a failure to simulate severe functional losses among standardized tests (e.g., Timed Up and Go, grip strength), and 'accurate' simulation of age-related impairments depended on the age of the participant[16].

Within this dissertation, age-matched SI and manual wheelchair user (MWU) groups were recruited. It was hypothesized that, similarly to Gerhardy et al.'s failure to simulate the effect of severe impairments on mobility task performance, the SI group would have differed mobility performance than the MWU group.

1.1.3 Incidence period of disability

Health trends in recent years indicate a rise in disability among the population approaching older age, with mobility as the most common impairment[7,38]. Those who age *into* disability are anticipated to have different lived experiences, levels of familiarity with community support, functional capabilities, and different medical access and support compared to those who age *with* it[21]. This discrepancy is hypothesized to result in significantly different skillsets and aptitude in wheelchair usage, especially as aging into usage coincides age-related cognitive and sensorimotor alterations[42,43,53,54]. Based on the ICF framework, Figure 1.3 highlights a number of anticipated group differences from the perspective of those with LL incidence, relative to EL incidence disability. However, these hypotheses have yet to be tested.

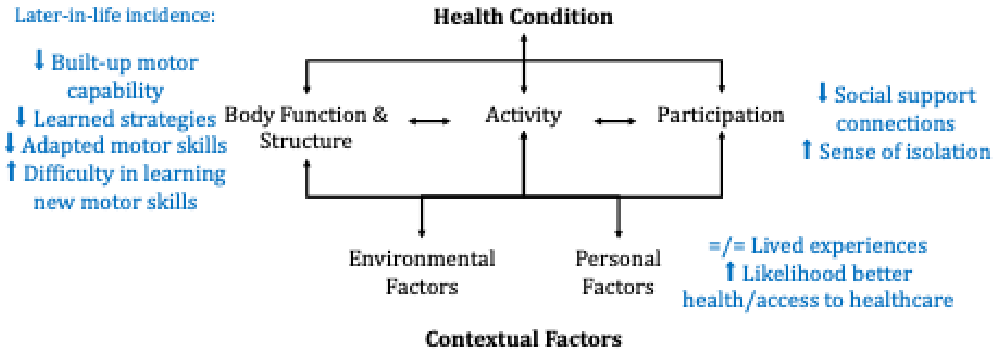


Figure 1.3: Anticipated differences that apply to those with later-in-life incidence of mobility disability compared to peers with earlier-in-life incidence; yet to be validated[21,24].

Yet, studies often recruit older adults with disability in convenience samples without categorization of incidence period, overlooking insights, for example, from the Ecological Model of Aging and Adaptation. hence, groups with differing capabilities will interact differently for the same task-environment demand[26]. While there are practical constraints (e.g., sample size, ability to travel), the impact of such a recruitment on inclusive recommendations is unknown[24]. For investigations on topics such as psychosocial pressures or long-term community programs, it has been argued that those aging with and into disability are comparable in terms of their societal needs (e.g., for rehabilitation services, long-term community support; note that a binary need is considered here rather than accounting for specific services of interest) and pathologies that impact both younger and older adults (e.g., cardiac diseases and spinal cord injuries impact both age groups)[46]. However, we hypothesized that there are situations, particularly in inclusive mobility, where different groups are necessary[55]. For instance, it has been shown that aging adults with recent incidence of disability reported greater self-limited participation and hesitation to request assistance even when they were unsure of their own ability to perform a task independently when compared to those who have had their disability for longer[25]. Further, as mentioned in the previous section, per universal design and ICF principles, different user groups will have different user requirements and support needs[21,24,55]. Hence, this work aims to fill this knowledge gap with respect to mobility performance and associated muscular exertions.

1.1.4 Influence of interventions

For any given task involving a human, three general types of interventions (i.e., modifications) may be made: an intervention to the task, to the environment or tools, or to the human(s) performing the task. Task interventions include changing the goal or applying administrative controls to the task procedures. An example of adjusting the task would be to provide one “normal” path and one accessible path or detour, as we often see in society today. Requiring persons with disability to access workstations, transportation or public spaces in a drastically different way than non-disabled persons would go against inclusion and equity. Hence for this dissertation, we assume the mobility task will not be modified via intervention.

To envisage the remaining types of interventions, we apply the Person-Press-Performance transactional model (PPP; transactional meaning an interaction between a person and a context; Figure 1.4) since the ICF does not model interactions of factors or impacts on performance[45,56,57].

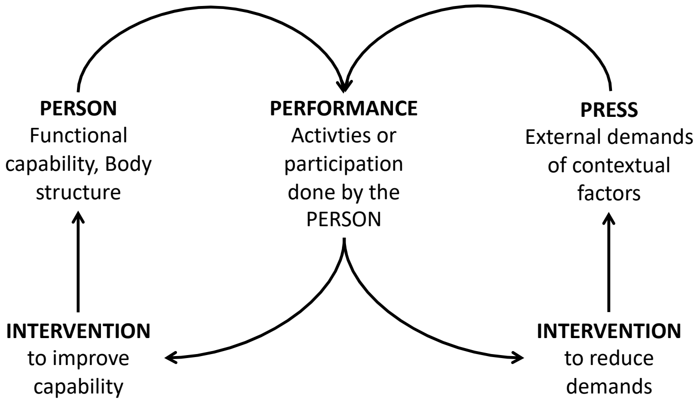


Figure 1.4: The PPP model[56,57]. Press includes both the task and environment demand; however, the scope of this research will not consider alteration task.

Person interventions (i.e., modifying the human) includes training; while known to be effective in the short-term, limited knowledge is available regarding the long-term[40,42,58]. Further, training can be inequitable with low retention rates[40]. Given the increasingly diverse socioeconomic profile of the aging population, an intervention heavily reliant on scheduling, access, and personal transportation to specialized locations may be less inclusive in nature compared to an environmental intervention[5,33,40].

On the other hand, environmental interventions include an increase of available space or the addition of screen-reader technology to signs[12,59]. In a study examining visual preference, Liu et al. (2021) found that spatial configurations that enhanced perceptions of “physical and psychological well-being” were well-rated and were positively correlated with the desire to repeatedly use that space[60]. In contrast, spaces like public transit associated with negative or unfamiliar psychosocial experiences may be self-limited, which place individuals at risk of isolation and reduced opportunities[25,61]. Interestingly, within the ICF framework, mobility aids like wheelchairs are included within the environment[45,62]. On the other hand, within the PPP model, ‘person-oriented’ interventions include improving or adapting human capabilities, and mobility aids like wheelchairs are considered to enhance a functional capability so it is thus included[56,57]. Most commonly, such ‘person-oriented’ interventions include the prescription of wheelchair training programs (e.g., Wheelchair Skills Test, Wheelchair Propulsion Test (WPT)) or alterations of wheelchair mechanisms (e.g., lever propulsion system, seat position)[37,63–65]. This dissertation will consider alternations to the wheelchair to be an intervention to the person, not the environment/press. The following example is intended to explain this decision:

Let’s say we wanted to apply an intervention to support the outdoor mobility for a wheelchair user. Switching traditional plastic or steel rear wheelchair wheels for carbon fiber wheels would not only reduce the weight but also reduce vibration transmission and therefore nausea and fatigue[65]. However, the burden of intervention implementation (e.g., cost, obtaining, maintaining) will fall to the manual wheelchair user[66]. On the other hand, alternations to the outdoor path surfaces can reduce bumps to create a more designated, smoother path, as demonstrated in Figure 1.5[67]. The burden of this intervention would fall to, for example, the city or institution owning the path. Note that such changes to infrastructure represent larger-scale interventions. Bear in mind that smaller scale interventions (e.g., coverings over sidewalk bumps) may also yield benefits.

Figure 1.5: (Left) A sidewalk example of an environment that does not support mobility aid usage, particularly wheelchairs, as the slope is uneven, and ledges are bumpy. (Right, two images) Examples of sidewalks that do support mobility aid usage. Note the level path and low incline slope that does not point into the street intersection. Reproduced from Clarke and Twardzik (2021)[67].

In the example, both interventions would be considered modifications to ‘environmental factors’ in the ICF framework. The former, in the PPP perspective, is a ‘person-oriented’ intervention with personal burdens, and the latter is a ‘press-oriented’ intervention with institutional burdens. Transactional models indicate that press interventions aim to *reduce* demand[57]. Placing intervention burden on the person does not reduce demand. Therefore, within the scope of this research, we consider the interventions to the wheelchair as a person-oriented alternation.

1.1.5 Human factors methods in accessible research

Human factors considerations within universal design have been encouraged towards improving equality within society[31,68]. However, a number of challenges and knowledge gaps exist therein. First, current product/environmental design practices typically address *accessibility* rather than *inclusion*; this may lead to inequitable access to opportunities and activities[24,49]. One well-studied example is the public transportation's paratransit systems. In providing the accessibility of paratransit, the economic and user burdens are greater than that of an inclusive public transportation system is projected to be[69–72]. Similarly, the provision of accessibility in ride-share and wheelchair training courses are limited by socioeconomic factors (e.g., location within a city)[40,41]. In order to effectively pivot universal design towards inclusion, a most-disadvantaged user group must be identified and actively considered[55]. From the ICF discussion in 1.1.3, aging adults the LL incidence of mobility disability are expected to face greater disadvantage compared to the general aging adult group, but mobility performance has yet to be studied in this context[46].

Second, traditional human factors evaluation methods have been shown to be biased when applied to historically excluded populations[73,74]. That is, users from these populations are prone to underrate their challenges, even in difficult situations[73]. Our own accessibility studies relating to public transit and autonomous shuttles similarly noted sentiments of "I could actually move into the [vehicle] now, therefore [the vehicle design] is good" regardless of any errors or safety concerns that occurred (e.g., collisions with the environment)[24,74]. These comments suggest a discrepancy between the perception of task execution and acceptable levels of performance and safety compared to objective performance. Such perception-action misalignments can compromise safety and/or comfort. This work proposes a means mismatch reduction by applying motor control concepts to investigate the perceptual factors underlying perception-action processes. The motor control concepts applied offer unexplored means of improving evaluation tool validity (e.g., NASA TLX) and overall mobility inclusion. These concepts are introduced in Section 1.2.

Finally, while design principles call for active communication with end users, the literature shows that SI is frequently used to test or investigate designs. One reason SI is popular is because it helps overcome time and budget conflicts in recruiting "difficult to reach" stakeholders or usability testers (i.e., people with disabilities)[75]. However, SI has been known to present numerous drawbacks that go beyond the design and human factors evaluation process. Put concisely, SI leads to the exclusion and diminished valuation of disability and aging voices[18]. Despite these psychosocial concerns, it remains strongly assumed that SI holds validity as a pedagogical tool when applied to recreate the disability experience in design[15]. Furthermore, investigations of SI have focused on neither the validity within design and human factors evaluation outcomes nor the impact of lived experiences and learnt behavior on performance strategy[19,76–78]. As a result, the validity of using SI has not been tested within inclusive mobility research; the sentiment for which was echoed at our recent presentation to the 3rd Annual Center for Disability Health and Wellness Symposium[48,52].

1.2 Motor control: From perception to action

Human motor control and actions are derived from internal motor planning and sensorimotor feedback systems[79]. Initial motor planning occurs prior to any action execution and is driven primarily by top-down perceptions of our own capabilities, the environment, and a movement goal[80]. Following the initiation of the action, bottom-up sensorimotor feedback (e.g., visual) can provide the information necessary for motor adjustment towards meeting the goal[81,82]. This process, applied to manual wheelchair movement, is summarized in Figure 1.6

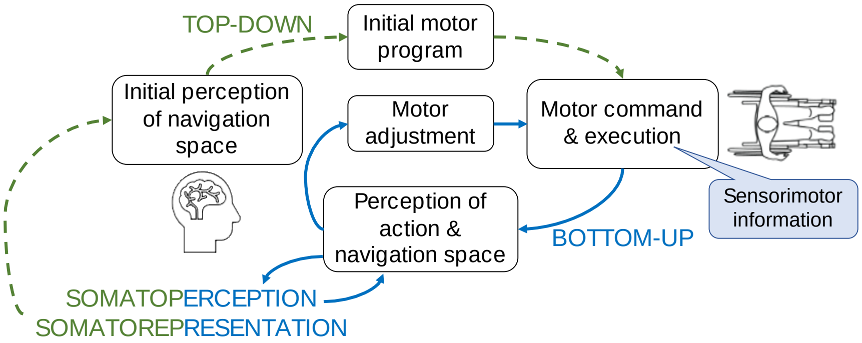


Figure 1.6: The motor planning and action loop. Dashed lines and solid lines represent processes associated with top-down and bottom-up sensorimotor perception, respectively.

1.2.1 Somatoperception and somatorepresentation

Humans perceive their body from both sensory information (i.e., experiencing stimuli) and cognitive processes (i.e., representations of the body with respect to knowledge and memory)[83,84]. Within motor control theory, explorations of *somatosensation* seek to describe the underlying mechanisms. For example, cutaneous stimuli generate tactile sensations which can be coded as spatiotemporal information then used in decision-making and motor adjustment[85]. Of relevance, reduced somatosensory capability is common among aging adults, which is a contributing factor to mobility loss[86,87]. While the negative influence of somatosensory decline on mobility impairment is out of the scope of this dissertation, *somatoperception* and *somatorepresentation* are considered to interpret mobility performance. These functions are considered as part of the ‘Body function & structure’ box within the ICF.

Somatoperception refers to the perception of one’s body (i.e., size, location, shape) and also objects in contact with the body[83,88,89]. These sensations may be described as ‘what your body feels like’[88]. For example, Creem-Regehr et al. (2014) utilized illusions to distort the visual length and shape of participants’ arm and hand to manipulate somatoperception. Authors found that visually induced illusions of body segments affected decision-making related to their movements, despite participants’ knowledge that their acting limb was in fact unchanged[89]. In a similar tone, SI has been presumed to alter participants’ decision-making enough to represent real impairments. It is worth noting that somatoperception concepts have not been explicitly applied in support of SI; rather the ‘logic’ that humans act based on how they perceive their bodily affordances has been used to assume validity. However, SI lacks the lived experienced and learned strategies of people who have used a manual wheelchair for prolonged periods[15]. Natural changes in aging that impact somatoperception, such as decline in proprioception, will also likely be reflected by mobility tactics differences between SI, EL, and LL groups[90,91].

Somatorepresentation refers to the cognition of what one’s body is believed to be like, based on knowledge and beliefs about it[83,88]. Within this concept, emotions “about” the body (e.g., “How do I look?” or “How do others think I look when I perform this task?”) impact motor planning and adjustment[83]. Further, alterations in somatorepresentation due to prolonged disuse of certain muscles for a task (e.g., legs in mobility) as well as negative emotions about the body may skew representations of body and actions[92]. This property of somatorepresentation suggests motor control differences between people who live with a disability vs. those who simulate the impairment. Yet on the other hand, literature shows that as people’s body changes, their representations of the environment changes as well[89]. Therefore, in our novel investigations of SI and incidence period impact on mobility performance, somatorepresentation needs to be considered.

1.2.2 Top-down motor planning

According to motor control theory, initial motor actions are driven predominantly by top-down perception of the task-environment[93]. A person performs sensory sweeps searching for cues using goal-directed attentional focus and existing motor programs (i.e., what the person knows to focus on from experience or existing knowledge)[94–96]. Figure 1.7 depicts a cat that wants to jump onto a table; it has scanned the environment for known cues, in this case various dimensions of the table and angles. Like the cat that has a motor program (also called “internal representation”), a person can preemptively be aware of what cues to seek out and what sequence of motor actions are anticipated to follow[93]. Posner (1980) cued participants on locations of upcoming stimuli and showed that humans were able to selectively adjust their attentive selection process to seek out the hinted cues[96,97]. In another type of cuing experiment, Lee et al. (2017) showed that a trip or slip recovery motor program could be triggered within 250 milliseconds of an alerting cue although the trip or slip was unpredictable before the cue[98]. These results showed that a cued task can enable the recall, extraction, and application of a motor program in differing circumstances given a familiar cue. Thus the literary consensus is that performing a task without a learned motor program or submitted to an unpredicted perturbation present greater uncertainty since action parameters and cues may be unknown[80].

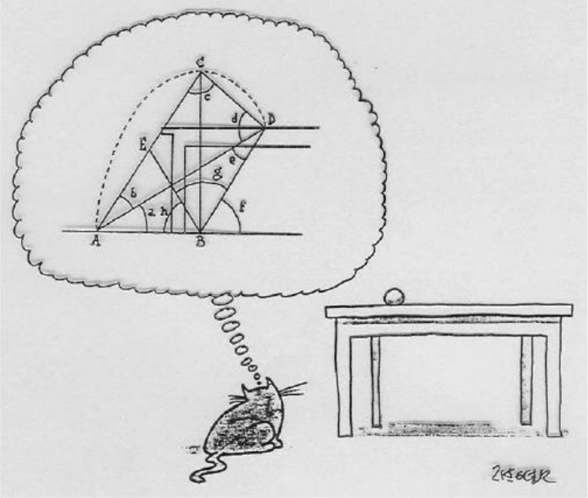


Figure 1.7 This cartoon illustrates computational analysis to perform a task with known motor action parameters but with an untrained program (hence, calculations are required). Image from The New Yorker as reproduced in Rosenbaum et al., 2010.

Recent findings argue that sensory sweeps may also be involuntarily influenced by salient stimuli, known as attentional captures[97]. Attentional captures can be leveraged to supplement a voluntary scan, and in the absence of a learned motor programs, passive support from the environment may facilitate the generation of actions. Such a strategy has great potential to reduce initial movement errors while improving safety and self-efficacy. However, need-based contextual cues and the extent adequate stimuli must be investigated to avoid overwhelming the users. One key point of investigation includes how modified stimuli impact motor program properties like relative timing or overall motor force[93].

Following logic set forth by the ICF, the efficiency and execution of motor programs are anticipated to be dependent on disability incidence. For example, people who age with disability may have developed strategies for movement and may become confused by an overabundance of cues[21,49,97]. While the type of information older adults use in perceiving space has been investigated, the impact of the resulting motor programs on design/human factors evaluation bias (e.g., workload) has not been investigated for adults with disabilities[31]. Nevertheless, it is commonly accepted that alterations in sensorimotor capability and motor learning affect performances of the aging population[42,53,54,99,100]. Bian and Andersen (2008), for example, found that older adults exhibit decreased reliance on ground surface information when presented simulated 3D spaces, potentially highlighting a cause of increased risk to falls or vehicular accidents[100]. Cognitive, proprioceptive, and sensory systems also decline as humans age[43,54,91,99]. Consequently, such age-related functional detriments that arise alongside shifting or worsening mobility function (and in worse cases, disability incidence) would necessitate the learning of new motor programs at a time when it is more difficult to obtain new, long-term gross motor skills[42,80]. This adds to the personal burden of aging adults. In practice, persons who age into mobility disability are anticipated to be less likely to possess or learn new motor programs and may hence benefit from augmented environmental cues.

1.2.3 Bottom-up sensorimotor feedback

Bottom-up sensorimotor feedback refers to the perception of an executed action derived from information about body with respect to the environment- as indicated with solid lines in Figure 1.6. Feedback is used in a closed-loop system to adjust subsequent movements[80,82,101]. As with top-down prediction, motor, sensory, and cognitive capabilities used in bottom-up perception are diminished with aging[43,44,54]. For example, a visual cue used in youth may become less salient or perceptible in older age due to visual acuity decrease with age[43,53,54]. Manual wheelchair users who aged with their disability are likely to experience these detriments gradually over time, thus using time and experience to adjust their motor programs[21,102]. On the other hand, those with LL incidence of disability may benefit more from environmental stimuli that augment useful action feedback. Kita et al. (2013) developed a transcutaneous electrical nerve stimulation system and demonstrated that utilization of the associated sensory feedback improved motor performance in a patient with severe sensory loss, and the motor ability persisted after training concluded[103]. This concept may be applied to motor programs in manual wheelchair propulsion. Specifically, enhancing a closed-loop mode of motor actions is likely to promote the reduction of errors in goal-oriented movements[80].

However, it has been argued that sensory feedback within a closed-loop sensorimotor system may not be necessary for movement monitoring or motor learning[104]. For this, motor imagery, the act of mentally but not physically executing a task, drives learning[104,105]. Ingram et al. (2019) demonstrated that novel and complex movements can be learned and executed in the absence of sensory feedback. Logically, such motor imagery requires one to perceive their own motor capability at a representative level. However, aging adults experiencing alterations of motor and cognitive functions may not accurately perceive their capabilities, particularly if they are at greater risk of self-limited participation, which further limits their experiences, like those with LL incidence of disability[21,25]. Due to this age-induced distortion, motor imagery may not improve motor performance for those who age into disability.

1.2.4 Muscular activity and exertion

Besides kinematics and kinetics, an important path to understanding motor actions and performance is via electromyography (EMG)[81,106]. Hence the signals from dominant upper limb muscles involved in wheelchair manipulation will be exploited to analyze exertion levels and wheelchair control behaviors. Surface electromyography (sEMG) is a noninvasive means of measuring muscular activity and deriving normalized exertion as well as contraction pattern parameters through signal processing techniques[81]. Such analyses are significant since high exertions and/or uncoordinated activities, particularly for manual wheelchair usage, may lead to the development of musculoskeletal pathologies (e.g., rotator cuff tears or tendinopathy); and co-

contraction and activity can yield insight regarding muscular magnitude, timing, and control[107,108].

sEMG has been used in manual wheelchair studies[49]. A number of studies use muscle activities as predictors for pain, rehabilitation purposes, or prototype usability testing. For example, one study utilized four-minute long propulsion efforts to examine EMG outcomes between push rim drive versus lever drive wheelchairs[63]. The different muscle activation profiles allowed physiotherapists to offer varying rehabilitation programs based on which muscles require training. Other studies rely on forward dynamics simulations or simulated impairment to investigate associated muscular activity; however, neither may reflect the anthropometry or capability profile of people with disabilities[50,109]. EMG measurements have permitted the identification and cataloguing of dominant muscles in wheelchair propulsion for a variety of propulsion techniques (e.g., single loop, semicircular)[109].

To investigate injury pathology, a number of studies involved high exertion tasks, such as propelling up a ramp with a steep slope (e.g., Figure 1.8) or wheelchair athletic actions [50,110]. While important towards preventing injury, such studies cannot be generalized to non-extreme daily mobility tasks, such as moving on level ground within a work or public space. Further, wheelchair athletes cannot represent the general population, particularly aging adults with recent disability onset. Hence results based athletic performances are beyond the aims of the present work, which focus on wheelchair users from the general population and to observe and analyze non-extreme mobility tasks that might imitate tasks encounter in work or daily settings.

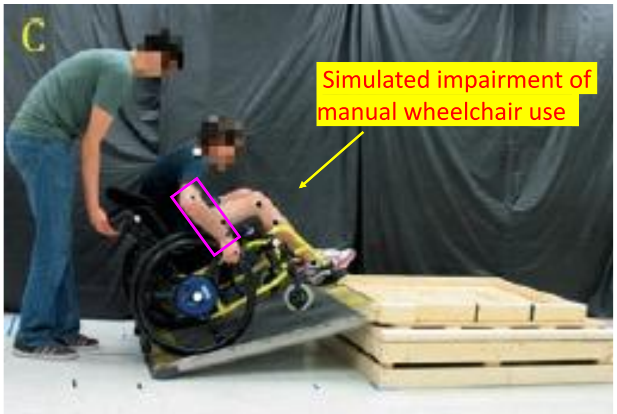


Figure 1.8: Example of a ramp propulsion with sEMG sensors placed on the subject. Modified image to highlight sEMG sensors on the upper arm and the use of SI, from Bertocci et. al[50].

1.3 Thesis structure

Chapter 2 will present traditional and proposed methodology utilized in this dissertation. Concepts introduced in this chapter will be integrated, and study aims are presented. Chapter 3 addresses, via a survey, the assumed mobility performance associated with a top-down representation of familiar MW tasks. (**H2**). Chapter 4 compares mobility performance between a sample population simulating MW usage with a sample population of MWUs in a maneuverability baseline task (i.e., parallel parking) (**H3**). Chapter 5 applies knowledge gained from Chapter 3 to design top-down and bottom-up environmental interventions and evaluates their influence on aging MWUs (**H1**). Chapter 6 utilizes the data from Chapter 5 to explore group differences when considering the incidence period of MW usage (**H1**, **H2**). A group simulating MW usage is also included in Chapter 6 (**H3**). Chapter 7 provides a general discussion and conclusion, including comments towards future work. A summary of participants is available in Appendix A.

1.4 Summary

A knowledge gap about the expected influence of perception-action misalignment for people who age into and with mobility disability exists, in addition to a similar issue that is likely to invalidate the utilization of SI as a convenient sample in the evaluation of performances by these groups. While hypothesized differences between the two incidence period groups may help partially bridge this gap, true differences have yet to be validated within the context of mobility. However, as traditional evaluation measures (e.g., NASA TLX) have recently-known biases against populations with disabilities, they cannot be solely relied on to address this gap. This work is anticipated to have broader impacts in improving the validity of environmental design processes, with emphasis on understanding underlying human motor functions. Hence, this dissertation also seeks to investigate the validity and any resulting bias from simulated impairment for task measures that are largely physical in nature. Following ICF principles and universal design guidelines to identify relevant user groups – this work aims to examine the impact of incidence period on user needs with respect to mobility performance and associated muscular exertions.

Chapter 2 Novel Methods Incorporating Motor Control Theory to Design and Evaluate Interventions

The knowledge gap at the intersection of disability, aging, and the associated systematic biases within traditional subjective measures prompts novel means of investigating inclusive mobility[111]. Motor control theory provides a promising, innovative approach through the consideration of internal representation of tasks, motor planning and execution, and sensory feedback. As such, we propose to utilize existing methods for task evaluations (e.g., NASA TLX) in combination with motor control outcomes (e.g., sEMG) at key points along performance. Doing so is expected to yield insight on how estimated and effective performance mismatches may be reduced and how effective mobility performance may be supported through augmented feedback[111,112]. It is assumed that enhancing task spatial perception can contribute to improve performance.

2.1 Why incorporate motor control theory

As presented in Chapter 1, human motor actions and control are derived from internal representations and consist of motor execution planning and sensorimotor feedback systems[79]. The planning is driven primarily by top-down perceptions of one’s own capabilities, the environment, and the task at hand- in this case, wheelchair navigation. Sensory feedback (primarily visual, within the scope of this dissertation), on the other hand, provide the bottom-up information necessary for motor adjustment(s) following an initial action[81,82].

Physical, cognitive, and sensorimotor capabilities are reduced with age[43,53,54]. Thus, a person's ability to perceive their own capabilities and performance may likewise be affected. These functional shifts are anticipated to impact the internal task representation and the selection/adjustment of motor programs to fit a perceived task (e.g., how much force magnitude and exertion duration are needed)[93]. Yet study recruitment practices that focuses on health condition likely overlook relevant ranges in functionality, specifically:

(1) The needs of older adults who age into a mobility disability, may be missed[7,42–44]. From a motor control perspective, older adults in this group may have more difficulty (i.e., less ability) to select or adjust motor programs for novel situations. Poor planning and motor adjustment due to reduced sensorimotor capability can negatively impact confidence, as shown by reduced self-efficacy from uncertainty in novel situations (e.g., being unsure one can independently move/stay balanced onboard a bus when unaccompanied)[25]. However, as recruitment practices in investigation studies do not typically distinguish this population, little is known regarding the effects of altered motor control abilities on this group's mobility performance[21,24,46].

(2) Simulated impairment (SI) is often utilized to replace hard-to-reach populations with a more convenient sample through temporary simulation[15,18,75]. This practice is commonly applied in endeavors relating to aging adults and people with disabilities, including for sEMG investigations and usability ratings. However, the use of SI has not been validated for the evaluation of mobility performance[48]. From the motor control perspective, sensorimotor skills likely differ between manual wheelchair users (MWU) and SI users. Stimuli utilized by SI users may not align with those used by

actual MWU, and design decisions made using simulated results may thus not have the inclusive impact desired.

The methods proposed for this dissertation examine the influence of visuospatial augmentations within the environment and further attempt an exploration of motor actions and control differences between groups of participants based on incidence period and SI.

2.1.1 Parsing top-down and bottom-up perception

While important to discern, identification of wherein the motor execution cycle (i.e., Figure 1.1) group differences may be difficult with traditional evaluation methods of environments or interventions (e.g., usability ratings). Motor control is commonly examined through measures of effectiveness or efficiency (e.g., task times, muscular exertion). However, within the realm of MW studies, no specific attention has been paid to determine whether top-down (TD) or bottom-up (BU) perception contributed to the outcomes. Rather, usability has been viewed as a broader concept independent of motor skills[113]. Yet, this knowledge can provide crucial information towards recommending performance-based accommodations that are more useful compared to currently-popular prescriptive accommodations (e.g., prescribing a minimum measure requirements such as ‘a 36in width doorway’)[114].

In short, TD and BU perspectives shed unique insight on motor program selection, adjustment, and execution. To parse TD and BU perspectives in the present work, a series of measures will be recorded before and after task completion, respectively. Validated measures for usability- comprising of effectiveness (i.e., completion), efficiency (i.e., critical events; NASA TLX; Environment Utility Measure), and satisfaction (NASA TLX; Environment Utility Measure)- will be used to allow results to be compared or extended in future studies[61,111,113,115,116].

It is important to note that several subjective methods for evaluating usability were used to avoid the potential biases associated with each method (e.g., ‘I completed the task, therefore I did well; regardless of errors committed’). [24,73,74]. Specifically, to quantify biases, subjective measures may be compared to objective measures. For example, critical events and surface electromyography (sEMG) relationship will be explored, as discussed further in the next section.

2.1.2 Measures for exertion

Monitoring the muscular exertion provides objective data to compare against the subjective scales used. sEMG measures specifically may be compared to NASA TLX scales for workload. Dominant muscles in wheelchair propulsion were identified across multiple wheelchair propulsion patterns. They include the biceps, triceps, anterior and posterior deltoids, and their respective activity recorded; images corresponding to the placement of electrodes are depicted in Appendix B[109]. It should be noted that the evaluation of EMG signals was not intended to quantify force during MW propulsion but was rather used to distinguish muscular activity duration as a function of experimental conditions and/or population groups (incidence period). EMG results were quantified as a percentage of maximum voluntary exertion obtained in standardized conditions.

Both the ICF framework and the literature on gross motor capability in aging adults suggest differing skill levels between the incidence period groups[21,22]. However, since this has not been validated in context, an initial examination of effective movements and sEMG data and subjective exertion ratings will be explored in the present work. An additional benefit of this mixed methods approach is to hear from disability and aging voices about learned strategies, which will likely uncover what information traditional methods may have overlooked[117–119]. The expectation is that this information will evidence discrepancies between performances objectively assumed or considered to be poor (e.g., high error rate, high shoulder muscle exertion) but rated favorably (e.g., low effort, high performance quality)[24,73,74]. Altogether, this novel method intends to introduce a mean of exploring motor actions selection, adjustment, and execution between groups[93].

A path-following task was selected and used for all studies in this dissertation. The path was physically reminiscent of a narrow corridor but intended to also represent the parameters within tightly furnished spaces. Multiple participants expressed that they experienced similar constraints within local restaurants, offices, and wide hallways with boxes or chairs placed along the walls (e.g., Figure 2.1). These comments anecdotally show that even though buildings are deemed "accessible", inaccessible situations may exist.

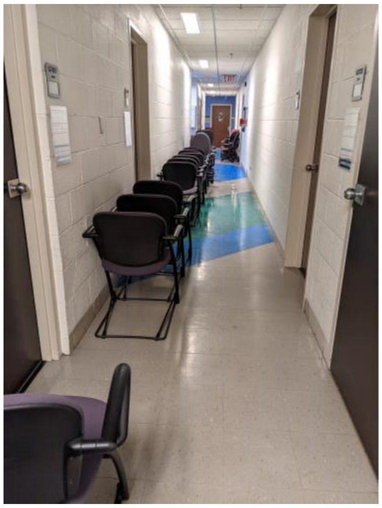


Figure 2.1: A hallway at the U-M IOE Department where studies were conducted lined with chairs during construction. While the situation was temporary, MWUs may have benefited from additional support in the remaining area. *Note: In the absence of such support, the obstacles were moved to another location by our building manager upon notice, however not all locations are able/willing to remedy such situations.*

2.2 Aims and conducted studies

The dissertation project was divided into three phases corresponding to specific aims. The flow of studies is presented in Figure 2.2.

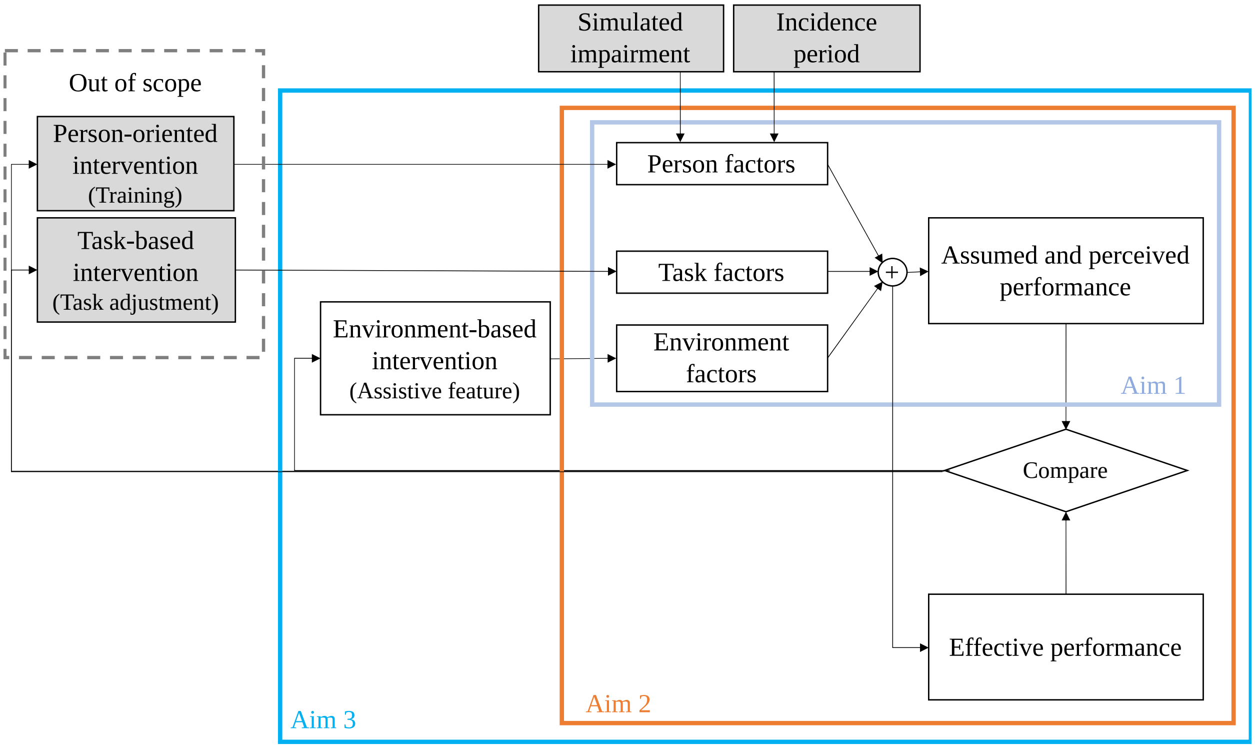


Figure 2.2: Concept map of the research completed, divided into three aims.

Aim 1*. To identify experience and environmental factors that impact subjectively assumed path following performance among aging MWUs*. TD perception reflects the selection and adjustment of learned motor programs /established internal representation of tasks. To achieve this, a survey asked wheelchair users to subjectively estimate their performance in a series of path-following tasks. Differences between incidence periods are tested. Environmental factors were selected based on validated wheelchair training programs. Factors concerning MW experience, independent usage, and general demographics were also considered.

Aim 2.1*. To examine discrepancies between effective and assumed path following performance for aging MWUs; and between incidence period groups (exploratory)*. Participants were recruited to complete a series of path-following tasks using a MW. Path-following tasks similar to those experienced in ADL (Aim 1) were simulated in a laboratory setting. TD perception was examined using subjective ratings prior each task. BU sensorimotor feedback was examined using observed task measures (i.e., critical event count, sEMG) during each trial and subjective ratings after each task. Subjective ratings were compared to effective measures to identify mismatches and uncover the potential biases within traditional usability tools (e.g., NASA TLX).

Aim 2.2. *To examine the validity of SI when estimating MW performance.* Participants were recruited to complete a parallel parking task. The task was tested in laboratory setting to simulate a task evaluated in Aim 1. The minimum total clearance required to perform this maneuver was collected and upper limb sEMG were recorded. Analyses compared the MWU group to the SI group. Subjective measures are beyond the scope for Aim 2.2.

Aim 3: *To test environmental interventions and investigate their impact on path-following performance for aging MWUs; and between incidence period groups (exploratory).* Path-following tasks from Aim 2 were adjusted to include environmental interventions (i.e., signage for augmented TD information; transverse markings across the path width and a midline marker for augmented BU information). The interventions were based on Aim 2 results. Analyses compared performance measures (i.e., critical event count, sEMG, subjective ratings) before and after intervention application.

2.2.1 Target population and recruitment

As discussed, recruitment was not to be controlled by health condition. Further, controlling by health condition would impose restrictions on the sample size too greatly and cause challenges in achieving an acceptable sample size. An initial, informal estimate of MWUs within the Ann Arbor area was conducted via Michigan Medicine’s Data Direct program through the geriatric center and yielded approximately 17,000 outpatients who used a MW between

2019-2021; a Med-IRB was not obtained thus this estimate provided the team with neither health details nor contact information.

A range of age cut-offs has been used in literature to define an older adult[49]. As the rise in mobility disability incidence has been observed within aging adults between the ages of 50-65 years and that the impact of gross motor skill decline is observed from roughly mid-40s onwards, the minimum recruitment age of 50 years was appropriate for our study aims. Further, amid the impact of COVID-19, recruiting volunteers exclusively over the age of 65 years was anticipated to be extremely difficult and risky. Hence, the age cut-off was set to 50 years.

From the recruited sample, incidence period groups were created for exploratory analysis. These groups were defined with a cut-off age of 45 years upon MW usage. This age was selected to avoid overlap between incidence age and years of experience predictors. Classifying individuals by years of experience may be misleading. For example, two individuals with 10 years of experience may not have comparable incidence ages in terms of a wholistic ICF profile (e.g., social connections, community access, employment demands). These latter factors influence wheelchair usage and impact of disability[45]. Furthermore, gross motor skills learning has been shown to trend downwards after the age of 40 years[42]. While short-term improvement of practiced gross motor skill performance following training appears intact and task-specific in old age, the longer-lasting effects of training on performance during aging have not been investigated[42]. Hence, grouping based on years of experience may also be misleading from a motor performance perspective. Thus, a dichotomous age cut-off was better suited overall. SI participants were within the same age group and used a loaner wheelchair available in the lab.

2.3 Impact of the COVID-19 pandemic

Project planning began in late February 2021 in the midst of the COVID-19 pandemic. Older adults were at an elevated risk of severe COVID-19 infection and long-term consequences. Further, older adults with disabilities, in particular, were also at a higher risk of reduced access to healthcare and transportation at a time when both of these essential services were greatly limited and/or unsafe. Therefore, with conservative health and safety measures, studies were conducted remotely throughout 2021.

Lab studies were planned with a high priority for health and safety. However, despite the University of Michigan and Institutional Review Board permitting the recruitment of older adult participants, many were reluctant to attend in-person sessions, resulting in a high cancellation rate (both due to illness and hesitance during waves). This was exacerbated by the inclement winter weather in 2021-2022 and growing difficulty in scheduling transportation through services such as A-Ride (Greater Ann Arbor’s paratransit service), senior transportation services, public buses, and on-demand ridesharing (all due to hiring shortages, rising rates, etc.). Multiple participants communicated these challenges to the research team. A number of data collection sessions were also cancelled due to research team illness or COVID-19 exposure.

All participants and experimenters were required to wear face masks during in-person data collection until Summer 2023. Experimenters continued to wear and recommend masks after the University requirements were removed. Masks may have impacted participant fatigue and levels of comfort during the mobility tasks. As such, additional rest breaks were given when requested. Additionally, while masks may have also affected verbal communication (e.g., muffled voices), recruitment criteria did not screen for auditory capability. To accommodate needs, all participant who communicated any difficulty in hearing to the research team (e.g., due to mask muffling or inability to read lips) were additionally given hand gestures alongside verbal instructions (e.g., counting on fingers during “3, 2, 1…Go”) and all communications were repeated as necessary.

2.4 Intellectual merit

Our novel framework seeks to highlight and distinguish TD and BU processes. This permits an estimation of capability-demand mismatches that may occur from a misalignment of internal representation of actions and functional capability resulting from the degradations of central and peripheral systems function from either aging or a sudden shift in capability due to disability incidence. Outcomes are expected to recommend types of interventions to mobility and to highlight some sources of mobility limitation in MWUs and further the understanding of internal representations of motor actions and effective performance.

Regarding incidence period, although group differences between those aging *into* versus *with* mobility disability have been speculated, there is a knowledge gap pertaining to quantified performance differences and the subsequent design of effective interventions. It has been thought that incidence would not impact mobility outcomes, however outcomes previously considered have been limited to binary measures of psychosocial distress and need for accommodations[46]. Such outcomes measures do not account for the range of accommodation effectiveness wherein those with more recent incidence are anticipated to have unique needs[25,55]. Regarding SI, recruitment biases have not been investigated despite “simulators” being a commonly used convenience sample[15,75]. In general, research utilizing SI acknowledge the limited generalizability of results; however, usability evaluations and design studies continue to use this method[75]. This work is a first step to address this issue and the surrounding knowledge.

2.5 Broader impact

Compared to our society’s current inclination towards person-oriented interventions (e.g., modification of personal mobility devices, training programs), the application of environment-based interventions is believed to be more inclusive and sustainable for the aging population[114]. This research is expected to support the ways in motor control can be used to directly target points of weakness in mobility. Results are anticipated to inform future user group definitions in universal design processes, effective TD and BU intervention strategies, and an awareness of recruitment biases within design and research. Addressing all these issues is urgently needed to guide the increasingly-popular adoption of universal design into accessibility endeavors[31].

Chapter 3 The Influence of Incidence Period on Manual Wheelchair Motor Planning and Perception

3.1 Abstract

The population of aging adults is increasing worldwide. Concurrently, mobility disability and manual wheelchair (MW) usage are both steeply increasing in adults aging in the US. Together, these trends effectively create two distinct and growing groups within older adults: those who age *with* mobility disability and those who age *into* it. However, the impact of incidence period on motor performance is unknown despite speculated differences that arise from lived experiences, inequitable training programs, and reduced self-efficacy with recent incidence. This knowledge gap can lead to biases in human factors usability and task/design evaluations. To primarily understand the impact of incidence period on top-down (TD) motor planning and perception, an exploratory survey was completed by thirty-seven adult MW users (MWUs) aged ≥50 years. The survey was offered online and via post to overcome COVID-19 limitations. Participants reported demographic and self-efficacy information and answered nine task scenario questions. Items were based on existing MW skills questionnaires. Incidence periods were defined as before or after age 45 MW incidence to account for aging effects on motor skills training. Subjectively estimated performance between those with earlier-in-life (EL) versus later-in-life (LL) MW incidence within constrained-width path-following tasks differed significantly. Performance scores were consistently estimated lower by the LL than the EL

group. These differences have implications on mobility self-efficacy and motor control, self-perception, and internal representation among those aging into disability.

3.2 Introduction

This initial investigation examined whether the relationship between subjective estimation of performances and task motor planning could differ as a function of experience in MW usage. In other words, whether mobility efficacy may be limited by an assumed TD motor process.

3.2.1 Mobility limitation and incidence

Mobility limitation is the most prevalent disability[6,31,32]. MWs are increasingly relied upon by aging adults to support mobility loss as access to wheelchairs improves and stigma decreases[34,35]. Yet, wheelchair training is inequitable and not always available or prescribed[38,40,41]. Additionally, the ability to train new motor actions and the impact of training are reduced by aging[42–44,120]. Hence, it can be hypothesized that those at the intersection of age-related slowing and recent incidence of MW usage experience greater limitations for independent mobility compared to those who have been affected by disability for longer[21,24,25]. For example, Cochran (2020) found that people with more recent incidence of disability have not developed the level of "resilience" as those who have lived with the disability for longer; thus resulting in a self-limitation of travel and lower self-efficacy in tasks [25]. Given this logic, a differentiation between MW incidence periods for older adults is necessary in order to define the widest range of useful stakeholders, as is recommended in universal design[55].

A motor control perspective is proposed to identify areas where assistive interventions may be effective. Current accessible standards largely focus on prescriptive minimum requirements that have been derived from *ad hoc* endeavors[114]. Such accommodations include spatial adjustments and the provision of assistance (e.g., personnel or assistive aids). Yet, many standards are insufficient in the face of our rapidly changing society and needs[49]. Further, accommodations focus on the overall movement and do not target underlying motor control systems that, in fact, inform movement[49]. This study focuses on the TD mode of motor control.

3.2.2 Top-down estimations of performance

Initial motor actions are driven predominantly by TD perceptions of the task-environment[93]. Sensory sweeps use goal-directed attentional focus, then existing motor programs are recalled and situationally adapted[94–96]. This initial motor program drives the preliminary expectation of performance and confidence[80,82,101]. It was therefore hypothesized that the reduced self-efficacy in older adults may be in part due to a mismatch between their TD assessment and estimation of mobility versus their effective performance.

One TD support that has been presented in motor control practice is called *attentional capture*. Environmental attentional captures can be leveraged to supplement the initial sensory sweep, however, useful needs-based cues must be investigated[97]. Administering subjective questionnaires (e.g., NASA TLX) *after* a task has been completed does not useful yield information regarding motor planning and, as recent findings suggest, may result in unintended bias for historically excluded populations (e.g., older adults, people with disabilities)[73,74].

3.3 Study aims

The aim of this preliminary study was to investigate whether the incidence period of MW usage impacts motor planning and perception for a path-following task across a variety of environmental factors. Years of MW experience was considered as a covariate. Subjectively *estimated* performance (i.e., performance *assumed* while the task was not actually performed) was assessed using visual depictions coupled with written descriptions of tasks. An understanding of TD ability to predict/plan performance as a function of incidence period and years of experience was intended to help inform TD intervention designs to be proposed in Chapters 5-6. This exploratory study is driven by the following hypotheses:

H1) Years of MW experience is a significant covariate for incidence period when predicting top-down estimations of performance.

H2) Estimated performance scores are lower for those with later-in-life (LL) incidence than those with earlier-in-life (EL) incidence of MW usage.

H3) For both incidence periods, TD estimated performance are lower for more complex than more simple maneuvering tasks.

3.4 Methods

3.4.1 Participants

Thirty-seven adults aged ≥50 years who self-reported manual wheelchair usage in at least partial support of mobility, independently or with assistance, responded to the survey. Screening was conducted either via email or phone. Exclusion criteria were:

- being blind or having significant, uncorrected visual impairment
- affected by significant cognitive impairment or spatial neglect
- affected by upper limb loss, upper limb prosthetic devices, or recent injury

Participants were recruited through the Disability Network of Washtenaw, Monroe, and Livingston (formerly, Ann Arbor Center for Independent Living) and online via the University of Michigan Health Research (UMHR) website. Participants from prior studies within the Sensory-Motor and Human Vibration Lab‘s internal database were also contacted. Age, MW incidence age, current biological sex (as opposed to sex at birth or gender identity), handedness, and visual capability were self-reported.

Table 3.1 summarizes the participant characteristics. Four participants were ambidextrous (two in each group), and two LL participants were left-handed. All others were right-handed. Only one LL participant reported "poor" vision. Ten EL and 21 LL participants reported MW usage due to medical conditions or accidents that led to medical conditions. Of the remaining six LL participants, two reported age-related usage (e.g., fatigue or balance) and four reported temporary situations (e.g., long-term recovery from surgery).

Table 3.1: Summary of participant demographics by group

	Earlier-in-life Incidence (Incidence age < 45 years)	**Later-in-life Incidence** (Incidence age ≥ 45 years)
Number of participants	n = 10	n = 27
Biological sex	Male: 3 (30%) Female : 7 (70%)	Male: 9 (33%) Female: 18 (67%)
Age (years)	61.3 (8.1) [50, 70]	60.7 (9.2) [50, 83]
Incidence age (years)	28.2 (11.4) [12, 42]	54.8 (9.8) [45, 79]
Years of experience (years)*	33.1 (11.4) [12, 55]	5.9 (3.8) (0, 15]
Weight (pounds)	191.1 (53.3) [118, 275]	207.1 (74.4) [94, 391]**

*Indicates statistical significance $p<0.05$.
**Two LL participants were noted outliers in weight, reporting 390, 391 lbs. body weight. The mean of all other LL participants was 192.4 (54.5) lbs.

3.4.2 Questionnaire design and procedure

The questionnaire (Appendix C) consisted of three sections: (1) general demographics, including self-reported biological sex, age, incidence age of MW usage, weight, and handedness; (2) MW experience and self-efficacy for a series of activities of daily living (ADL) related to MW usage; (3) subjective rating of performance for a series of graphically depicted path-following tasks. Existing in-person skills tests and categorical evaluations were adapted to the questionnaire format[121–123]. An instructions page, detailing key study information and allowance to complete the survey with assistance was included prior to the first section, and a compensation form was included after section three.

Section 1, General demographics. Categorical responses (e.g., handedness) and short textbox responses (e.g., weight) were presented. Body and MW-combined weight responses included numerical values. One LL participant did not report a combined weight but instead stated “using wheelchairs provided by transportation services”. Although this response could not be used in analyses, insight relating to MW ownership and usage will be considered and discussed.

Section 2, MW experience and self-efficacy; ADL tasks. Frequency of ADL and movement tasks utilizing MWs were solicited to estimate self-efficacy and thus understand subjects’ perception of their capability. For each category of use (Table 3.2), the participants state whether they typically utilized a MW for the respective movement “independently”, “with assistance”, or “not at all”. For responses excluding “not at all”, participants were subsequently required to report the frequency, ranging from “less than once per week” to “multiple times per day”. No illustrations accompanied the text.

Table 3.2: Basic ADL wheelchair categories of use included in the survey.

	Item
1	Move within a room, indoors
2	Move between rooms, indoors
3	Move through a hallway, indoors
4	Move within indoor workspaces (e.g., office)
5	Move within indoor public spaces (e.g., grocery store, hospital)
6	Move outdoors, along a sidewalk
7	Move outdoors, not on a sidewalk (e.g., grassy park, dirt path)
8	Move and travel in vehicles (e.g., taking bus or rail trips)

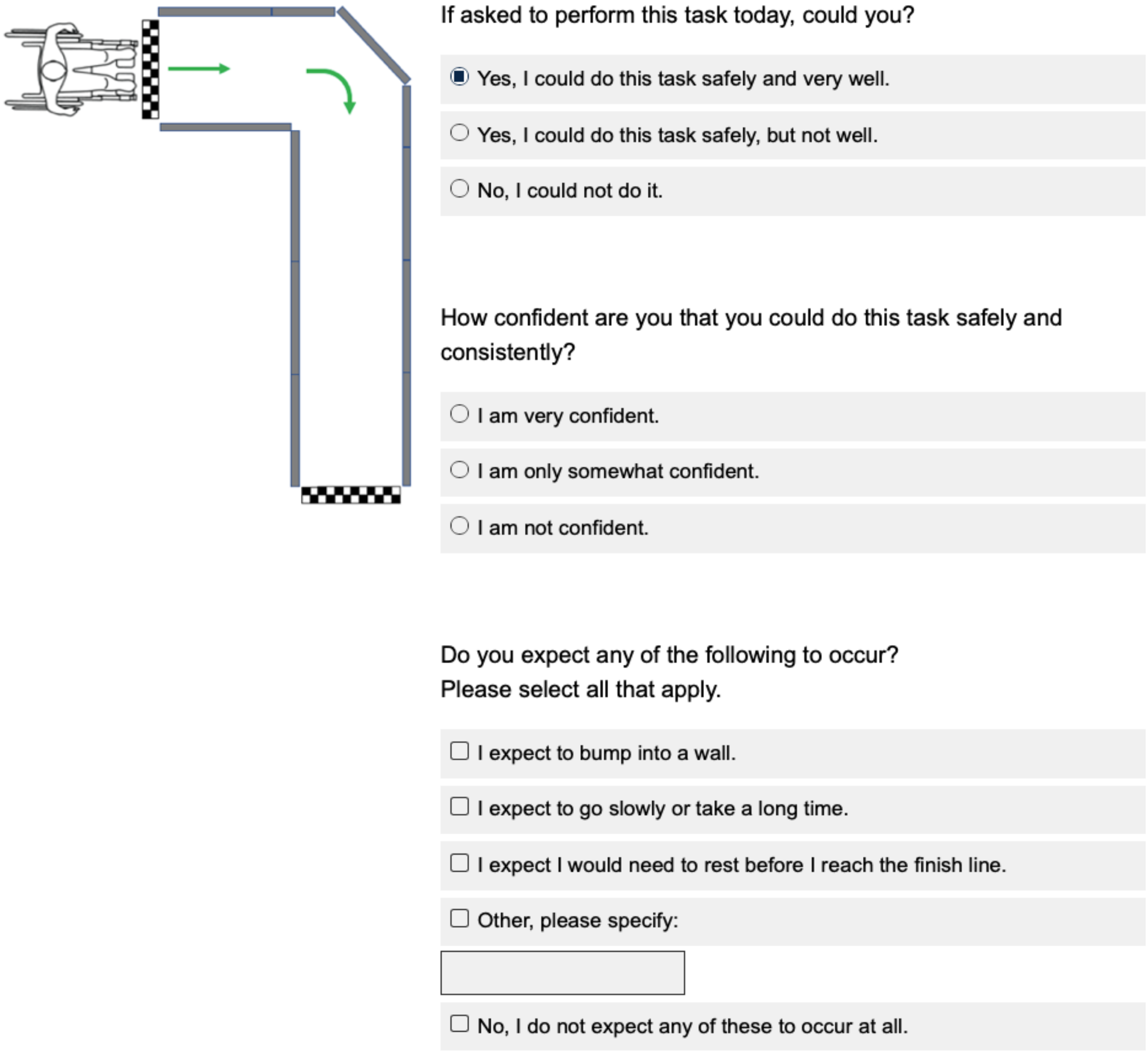
Furthermore, categories of use specifying common scenarios based on the Wheelchair User Confidence Scale for Manual Wheelchairs (WheelCon-M) were presented (Table 3.3)[121].

Responses were on five levels of self-efficacy, ranging from “Not confident at all” to “Extremely confident”. These questions did not include illustrations.

Table 3.3: Categories of use under common scenarios assessed as self-efficacy.

	As of now and on your own, how **confident** are you that you can move your manual wheelchair...
1	...over carpet?
2	...around furniture?
3	...over thresholds, such as at front doors?
4	...in small spaces, such as a bathroom?
5	...up a standard wheelchair ramp?
6	...down a standard wheelchair ramp?
7	...up a dry ramp that is steeper than usual?

Section 3, Subjectively estimated performance and confidence; Path-following tasks. Path-following task questions were presented to complement more specifically the internal representation of common ADL tasks with accompanying to-scale images (e.g., Figure 3.1). Questions were based on tasks performed in the Wheelchair Skills Test Questionnaire (WST-Q) and baseline performance tests in accessibility investigations[74,121–123].



If asked to perform this task today, could you?

● Yes, I could do this task safely and very well.

○ Yes, I could do this task safely, but not well.

○ No, I could not do it.

How confident are you that you could do this task safely and consistently?

○ I am very confident.

○ I am only somewhat confident.

○ I am not confident.

Do you expect any of the following to occur?
Please select all that apply.

☐ I expect to bump into a wall.

☐ I expect to go slowly or take a long time.

☐ I expect I would need to rest before I reach the finish line.

☐ Other, please specify:

☐ No, I do not expect any of these to occur at all.

Figure 3.1. Example depicting a task question requiring participants to consider performance, confidence, and potential errors. A written task description clearly highlighting Start and End points is also provided but not shown here.

Nine path following tasks prompted participants to rate their estimated performance and confidence. These ratings are summarized in Table 3.4: Nine path-following tasks including their respective movement components and lateral tolerance levels. As subjects are imagining the task, they rely only on their internal representation based on their motor and cognitive capability (i.e., motor planning). Three questions are linked to each task; wording and categorical responses are indicated in Figure 3.1. Within these three questions, estimated performance for each of the nine tasks was assessed via: (1) estimated effectiveness measures (completion of task), estimated self-efficacy, and estimated efficiency measures (binary anticipation of acceptable time to completion, anticipation of critical events).

Table 3.4: Nine path-following tasks including their respective movement components and lateral tolerance levels.

	Movement components				Lateral tolerance	
	Forwards	Backwards	Right-handed turn	Left-handed turn	6 inches	2 inches
Task 1	x					
Task 2	x		x		x	
Task 3	x		x			x
Task 4	x			x		x
Task 5		x	x		x	
Task 6		x	x			x
Task 7		x		x		x
Task 8	x	x	x	x	x	
Task 9	x	x	x	x		x

The nine path following tasks are categorized into *task types* defined by their movement components: forward movement with one right- or left-handed turn (e.g., the right-handed in Figure 3.1), rearward movement with one right- or left-handed turn, and parallel parks (which require forwards and rearward movements as well as both directional turns to complete). Rearward movements are indicated with a rearward facing MW at the Start line and with an orange arrow, as opposed to the forwards facing MW and green arrow illustrated in Figure 3.1. Each task is described for each of the two lateral tolerances (i.e., path widths with respect to the wheelchair), described as “2 inches (5cm) on either side” and “6 inches (15cm) on either side”. All paths are described as roughly 15 feet (~4.5 meters) in length; with exception of the simple, straight path which is described as 10 feet (~3 meters) in length.

A complexity measure was defined to differentiate each task type. Task types with corresponding max score and complexity level are summarized in Table 3.5. For example, the forward maneuver with one turn (e.g., Figure 3.1) requires two elementary movement components: (1) basic forward propulsion and (2) one turn, either left or right. Therefore, it was assigned a complexity value of 2. A parallel park maneuver was assigned a complexity value of 4 because it requires a combination of the four elementary movement components- i.e., at least one forward movement, one rearward movement, one left turn, and one right turn. Note that lateral tolerance is not a movement component, but rather relates to task difficulty instead of complexity. Therefore, the two lateral tolerance levels do not have complexity values.

Table 3.5: Maneuvering component descriptions, scores used in the analysis of H2, and complexity values used in the analysis of H3. The minimum score for each row is 0, cases where all tasks in that category were assumed incompletable

Task Type	Maximum Estimated Performance Score	Complexity
Overall (i.e., all nine tasks)	18	-
Straight path component	2	1
Forwards turn component	6	2
Rearward turn component	6	3
6in lateral tolerance tasks	6	-
2in lateral tolerance tasks	6	-
Parallel parking tasks	4	4

Due to the COVID-19 context, this survey was administered entirely remotely in order to prioritize the health and safety of older participants with disability. Hence, the questionnaire was designed to be easy to read and understand. Since the older US population was targeted, reporting weight, stature and path conditions was done in English units to reduce confusion. The study was approved by the U-M Institutional Review Board. All participants elected to fill the survey online via Qualtrics.

3.4.3 Analysis

Analyses compared older adults affected by EL vs. LL incidence of MW usage with respect to their subjective estimations of mobility performance. Incidence period groups were defined with a cut-off incidence age of 45years. This age was selected to avoid overlap between incidence age and years of experience predictors since classifying individuals by years of experience may be misleading. For example, two individuals who have used a MW for 10 years may not have comparable experience when viewed from a wholistic ICF profile (e.g., social community, employment opportunities)[21]. Furthermore, gross motor skills learning trends downwards after the age of 40 years[66]. While short-term practiced gross motor skill performance following training appears intact and task-specific in old age, the long-lasting effects of training on performance with aging have not been investigated[42]. Hence, grouping based on years of MW experience may also be misleading from a motor performance perspective, thus a dichotomous age cut-off was better suited overall.

For **H1**, a Pearson correlation between incidence period and years of MW experience was performed to examine the relationship between variables. This also served as the test of covariate assumption for **H2** (i.e., predictor-covariate independence). Dependence between incidence period and years of experience would exclude the possibility for a covariate analysis. For **H2**, a one-way ANOVA or ANCOVA (depending on **H1** results) was used to assess the differences in TD predictions of performance between incidence period groups. For **H3**, regression models for TD estimations of performance were generated to investigate the predictive capability of task complexity on estimated performance for each incidence period group. A Bonferroni-corrected alpha of 0.017 was used to test these three hypotheses.

Performance measures consisted of scores derived from responses to the path-following task questions. Responses of “Yes, I could do this task safely and very well.”, “Yes, I could do the task safely, but not well.”, or “No, I could not do it.” were given a numeric value of 2, 1, and 0, respectively. Predictors were years of experience, incidence period, maneuvering component, and complexity. Scores and predictors are summarized in Table 3.4.

Exploratory examinations of events assumed to occur during the task, participant independence, and self-efficacy were made without further interpretation of statistical significance, given the inflated Type I error. Trends and qualitative themes will be reported for assumed critical events and independent manual wheelchair usage between incidence age groups.

3.5 Results

3.5.1 Years of MW experience

The Pearson's correlation coefficient (EL = 0; LL = 1) indicates that the incidence period group and the years of MW experience were significantly corelated; r = -0.88, t(35) = -11.08 (p = 5.37e-13). Hence, our dataset is not appropriate for a covariate analysis since the predictor and covariate are considered dependent[124]. This relationship is due to a relatively small overlap in years of experience between the EL and LL groups. The overlap occurs in the 12-15 years of experience range. One EL participant reported 12 years of experience while all others reported at least 27 years of experience, and three LL participants reported 13, 14, 15 years, respectively, while all others reported less than 12 years.

3.5.2 TD estimation of performance

The subjectively estimated performance of the EL and LL groups are summarized in Figure 3.2. The normalized mean scores for each task type (defined in Table 3.4) are presented. The maximum score of 1 corresponds to an estimated perfect performance for all tasks in that respective type. The minimum score of 0 corresponds to an assumed "No, I could not [perform this task]" for all tasks.

The one-way ANOVA revealed that the Overall the TD estimated performance scores were significantly lower for the LL than EL group (**H2**), with F(1, 35) = 10.4 (p = 0.0027) and a large effects size of $\eta^2 = 0.23$. Visual trends between each task type (Figure 3.2) suggest that moving rearward or in narrow spaces may be particularly difficult for the LL group.

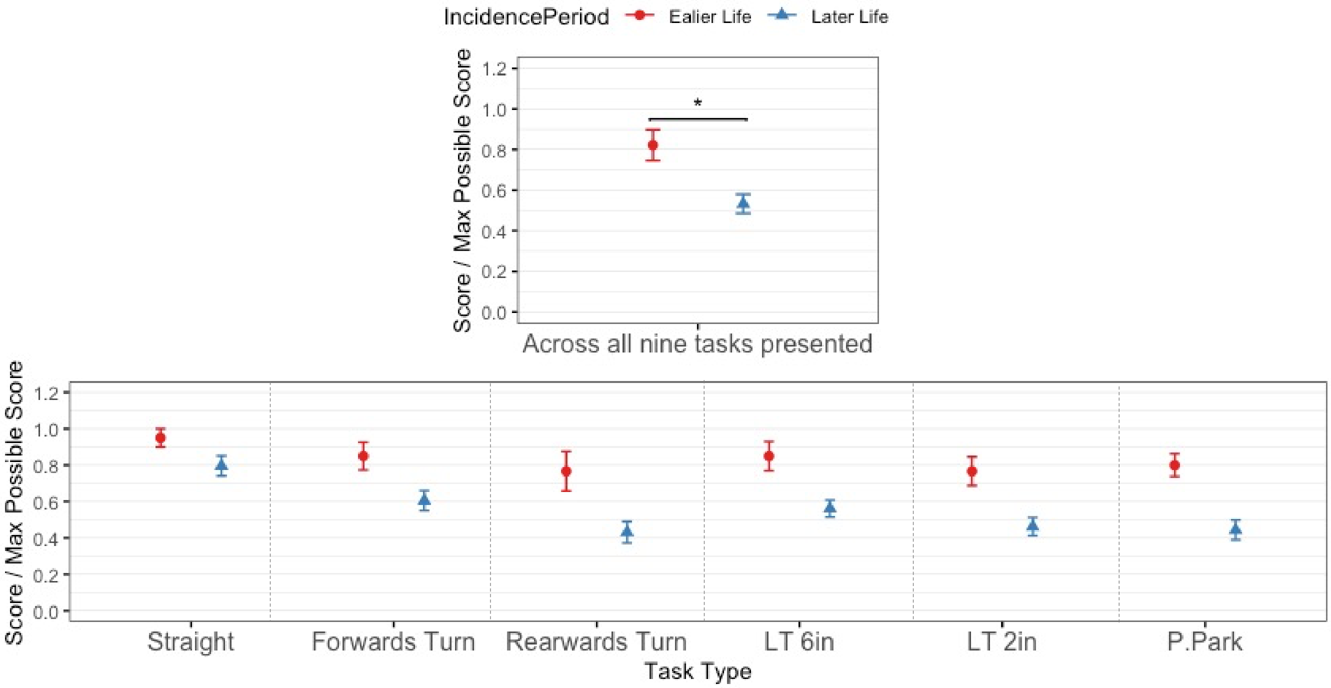


Figure 3.2: Subjectively estimated performance for each task type. Error bars denote standard error. (Top) Results from the grouping of all nine tasks across incidence period groups; (Bottom) Trends from each task type across incidence period groups. LT: Lateral Tolerance in inches; P.Park: parallel park

3.5.3 Complexity

The normalized TD estimations of performance for each complexity level are presented in Figure 3.3 with piecewise linear regressions, their corresponding equations and R^2 values. The regression between complexity values 3 and 4 exhibit $R^2 = 1$, by definition. A second-order polynomial trend was also examined with similar results, suggesting information of interest may be more simply drawn from the slopes of linear piecewise functions.

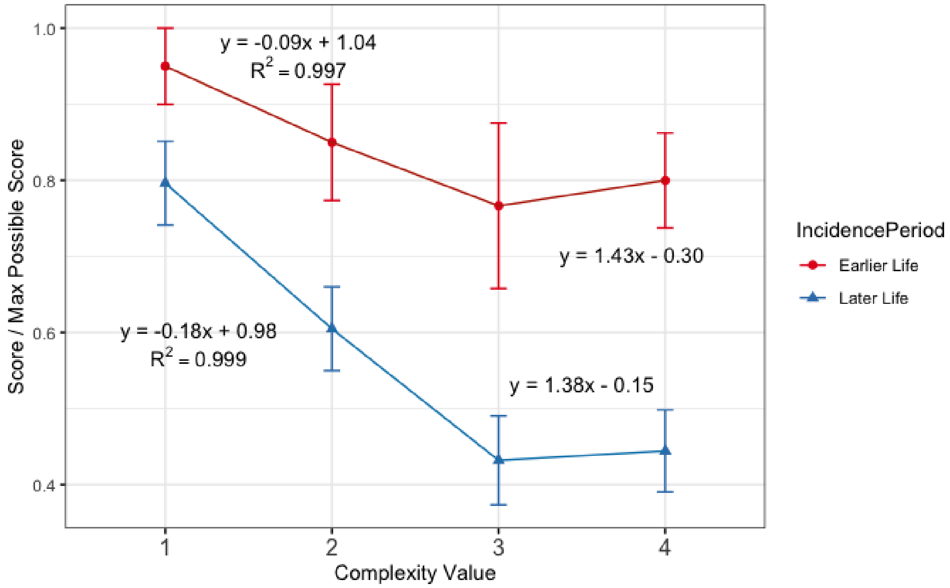


Figure 3.3*:* Linear piecewise regressions fitted onto subjective estimation scores for each complexity of task. Error bars denote standard errors.

The piecewise inflection point, estimated via the *segmented* package in R, is roughly 2.90 for both the EL and LL group ($p < 0.0005$). The decline in score with increasing complexity is steeper for the LL than EL, and the regression intersection the score ordinate is also lower for the LL than EL group. It was originally hypothesized that maneuvers requiring a combination of all base movements (i.e., complexity = 4) would correspond to the lowest score of performance estimation. However, in the present set of maneuvers, the results indicate that a level 3 complexity corresponds to a minimal score that does not appear to increase with an added complexity.

3.5.4 Exploratory trends

As indicated in Figure 3.1, each estimation of performance also required participants to report any events they assumed would occur while completing the task. The number of assumed-to-occur events was tallied and normalized for each task type and summarized in Figure 3.4. The maximum value of 4.0 indicates every event option was selected for all path following tasks; the minimum value of 0.0 indicates none were selected.

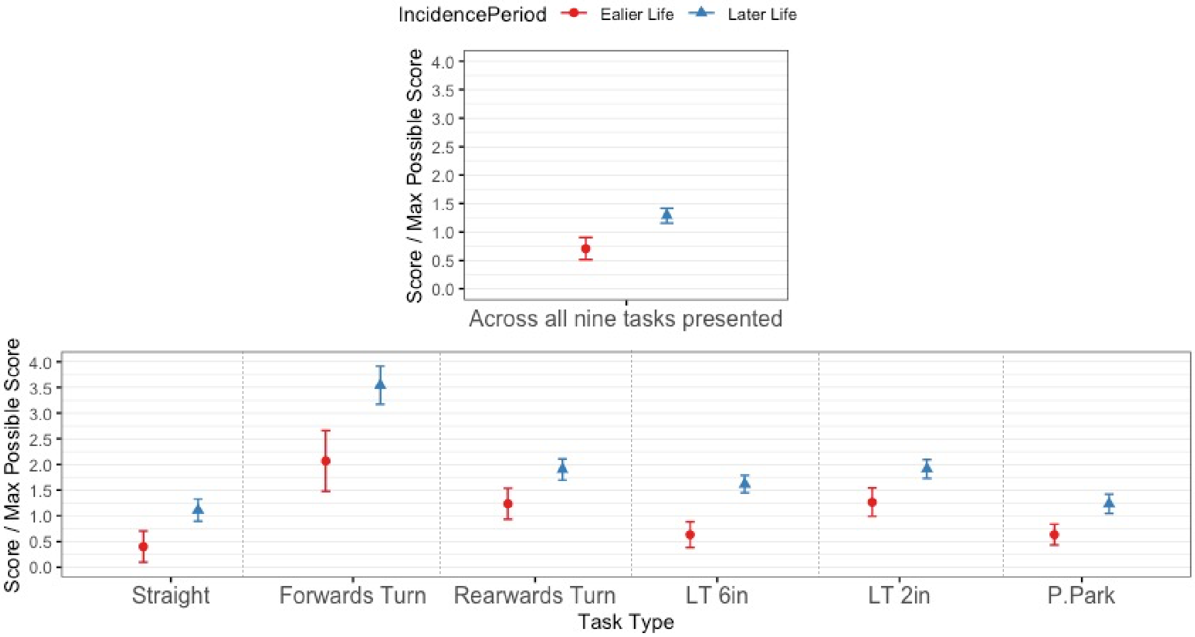


Figure 3.4: Mean number of assumed events per task type. Error bars denote standard errors. LT: Lateral Tolerance in inches, P.Park: parallel park

The Pearson's correlation coefficient between the TD estimated performance and number of anticipated events was r = -0.79, with lower performance correlating with a greater number of assumed events. "Other" events reported communicated exasperation with certain maneuvers (e.g., *"Complete frustration"*, *"I expect I would be vocally abusive towards my chair"*, *"I would be frustrated and would need help. I would probably be found crying."*). Qualitative responses were also received from the open-ended comments box at the end of the survey. Examples of comments are: *"[I have] restricted range of head motion", "I would need to back up at the corner and readjust", "I do all the tasks described and have damage to every doorframe, doors, and walls. I am considered good."*. Note that the content of these responses was not directly asked in the survey.

Lastly, trends in independence and self-efficacy were compared between groups[25]. Trends within Pearson's Chi-square tables revealed that the reported independent MW usage was lower for the LL group than the EL group in public and workspaces, within and between furnished rooms, through hallways, along sidewalks, and on transit vehicles. Yet neither the EL nor the LL group reported a greater reliance on assistance than the other in any scenario. Qualitative comments highlighted the inability by both groups to use certain spaces without assistance (e.g., *"Rolling around is difficult so my daughter takes me out. I'm nearly never out alone."*, *"I only use a wheelchair [...] when someone else may be pushing me or in a large museum or sports arena where I may or may not have assistance.")*.

3.6 Discussion

This survey investigated estimated performance for constrained path-following tasks as the first step to differentiate motor planning abilities (top-down process) between aging adults who either age into or with their mobility limitation. Statistical analyses were driven by three main hypotheses. Overall, the results strongly suggest significant differences between the EL and LL groups in the context of mobility performance and motor planning. This group difference is presumed to stem from a difference in the way in which tasks are internally represented (i.e., somatorepresentation) as a function of MW incidence period. Since both groups (EL and LL) are age-matched, group differences due to sensorimotor age effects may be excluded. It is worth noting that although functional capabilities were not considered, selection criteria used avoided the inclusion of participants affected by upper body limitations, hence group differences in functional capability to control a MW may also be reasonably excluded. According to the current literature, the incidence period is not treated as a relevant group characterization due to presumed similarities (e.g., a binary need of accessibility accommodations, being a target of stereotyping and stigma; as in Molton and Ordway (2019)). In this work, the combination of the ICF view on disability and motor control concepts (somatoperception and somatorepresentation) brings new results indicating that incidence period is a worthwhile sub-grouping of the general older adult and disability populations[21,22,45,46].

3.6.1 Estimated performance of tasks

3.6.1.1 Somatosensory processes inform differences

Although the overlap in MW experience between groups prevented an ANCOVA analysis, the ANOVA findings indicated that the subjectively estimated performance was lower for the LL than the EL group ($\eta^2 = 0.23$). Given this and known age-related reductions in functional capability with possible improvement of performance through training, years of experience may not be as strong a predictor for performance as incidence period of MW usage[21,42,120]. Figure 3.2 clearly indicates (visually) large gaps between both groups' estimated performance means in all categories of task. These gaps suggest incidence period-related group differences and supports the hypotheses that those who age *into* mobility limitations may have a disadvantage for independent movement when compared to others within their age group who aged *with* their limitation. This supports the examination of incidence period when considering mobility capability and skills.

In terms of motor planning, our findings suggest differing perceptions of capability and motor actions between the two groups-- pinpointing the source of differences is difficult here since the type of physical limitations, cognitive abilities, spatial abilities and motor skills were not evaluated with specific tests. However, it is suspected that internal representation of the task and spatial perception may differ between the two groups due to differences in somatoperception and somatorepresentation[83,88]. *Somatoperception* is a process of perception of self (i.e., introception) that stems from part of the sensorimotor system, specifically the somatosensory cortex[83,125]. This process impacts postural schema (e.g., 'how do I estimate my body would be postured in this motor program') and body referencing (e.g., 'how much space do I estimate my body would occupy in this posture and motor program'; 'where do I estimate collisions may occur'). It may be hypothesized that due to the reduced familiarity with MW usage, the LL group may experience lower confidence in their somatoperception, hence lower estimated performance. *Somatorepresentation*, on the other hand, stems also from the somatosensory cortex but deals with the construction and application of knowledge and emotions related to the body[83,125]. As people with more recent incidence of disability experience greater discomfort due to psychosocial factors (e.g., making a mistake; needing assistance in public), their somatorepresentation of their body and the execution of tasks are likely associated with more negative emotions (e.g., how do I look; how do I look in other people's perspective)[25,66]. Interestingly, negative emotions regarding one's somatorepresentation of the body have also been shown to have some impact on bodily representation, for example body size and occupied volume[92]. From the ICF framework, it is anticipated that people who age *into* disability may experience great unfamiliarity with their body and the disability community, and therefore the visibility and experience of disability, compared to people who aged *with* their disability[21]. Further, long-term use of tools to enhance bodily capability (e.g., the use of hand tools, as in Bassolino and Serino, 2022), impacts body representation[88]. Integrating this literature, it is postulated that skewed somatorepresentation within the LL group due in part to "emotional attitudes" may alter performance estimation. Note that while sensory inputs may also impact somatorepresentation, we controlled for visual impairments and spatial neglect. Hence, it may be assumed that differences in sensory perception are influenced by the incidence period[88]. Both somatoperception and somatorepresentation provide interesting and novel frames of reference to examine otherwise unseen pain points and potential areas for targeted interventions.

3.6.1.2 Task type impacts estimations

The similar relative group differences between task categories indicate that similar cues are being used to program motor actions by both groups (Figure 3.2). This interesting finding supports the notion that an inclusive intervention that supports motor planning for both groups can be found. However, since the LL group reported lower estimated performance, interventions must actively consider their needs to avoid falling short[55]. In this sense, incidence periods could be used to distinguish population groups when designing interventions; this consideration of the underlying mechanisms that govern mobility can thus improve intervention effectiveness.

Considerable gaps in estimated motor component skills were observed between EL and LL groups (see Figure 3.2), with the exception of the straight path trajectory. Rearward movement and parallel parking (the latter of which also requires rearward movement) corresponded to the lowest scores among the task categories (Figure 3.3). Less than half of LL participants anticipated to complete tasks including rearward component(s) (mean estimated performance score < 0.5). Rearward movement may likely be a motor action for which the LL group has yet to develop an adapted motor program. This assumption appears logical as few ('real life') scenarios require prolonged rearward movements. However, several of our laboratory study (see Chapters 5-6) pointed out both brief and long rearward movements within constrained spaces like transportation (e.g., maneuvering into securement spots, crowded bus) or restaurants (corner seating, cramped table layout)[24,48]. Unpracticed maneuvers, perhaps as an effect of being scarcely used, may cause psychosocial stress when attempted in public or cramped situations; not unheard-of, such situations may be avoided altogether, even at the risk of self-limiting opportunities[25,73]. Therefore, rearward movement scenarios such as the ones mentioned by participants can hint at activities that may restrict those with LL incidence from social participation.

As this study is exploratory, the source of the LL group's reduced perceived capability is difficult to determine. However, it may be supposed their motor programs for wheelchair maneuvers may not be refined, which is a simple conjecture given very basic trajectories addressed in the survey. This is supported by the qualitative end-of-survey comments (e.g., *"[I have] restricted range of head motion", "I would need to back up at the corner and readjust*). Here participants unknowingly revealed that the integration of capability perception was actively being utilized, despite not being directly asked. Hence, we may draw the conclusion that the LL group is aware of what motor program parameters are necessary to complete the task (e.g., recall the cat in Figure 1.7 considering parameters), but their motor programs are likely less defined and practiced compared to the EL group. This line of thought is further evidenced by the LL group's lower estimated performance yet similar relative differences between task categories compared to the EL group. As groups are age-matched, sex-matched, and self-reported no cognitive impairment, we anticipate limited impact due to age-related working memory or cognitive capability differences between groups. Interestingly, this points to a conscious integration of information to estimate performance; specifically of one's own functional capabilities and one's own experiences. It is reasonable, then, to presume that both the EL and LL groups have built internal representation of tasks including the general goals, factors, and cues available.

However, the LL group is significantly less confident in their skills. Follow up studies examined objective performance to compare perception of capability to effective capability between EL and LL groups (Chapter 6). Discrepancies between capability perception and attempted action can lead to unsafe mobility, and discrepancies between estimated and actual performance can biased usability evaluations, especially in earlier design stages where prototypes are of low fidelity[126].

Finally, Figure 3.2 reveals that both EL and LL groups predicted relatively low performance in situations with small lateral tolerances. While the lateral tolerance used in the survey were lower than the minimum clearance guidelines of the Americans with Disabilities Act (ADA) for hallways *construction*, multiple participants across all studies in this dissertation communicated experiencing extremely low tolerances in contexts such as hallway *use*, like obstructions from boxes, stand-up signs, or temporary storage[24,111,127]. While many such situations present movable obstacles, oftentimes the psychosocial impact of moving the items, asking strangers to help/relocate, or requesting assistance can lead to highly negative experiences and unseen pain points[15,49,68]. Further, commitment errors or salient events (e.g., taking a rest) while performing maneuvers in daily life may draw undesired attention to wheelchair users and be cause for distress. This is particularly concerning for the LL group as a high correlation was found between lower anticipated performance and assumed events.

3.6.2 Task complexity

The increase in maneuver complexity did not necessarily reduce the estimated performance linearly. In fact, maneuvers that required a combination of all base movements (i.e., complexity value = 4) and rearward base movements alone (i.e., complexity value = 3) were associated with similar performance scores , as seen in Figure 3.3. However, the regression slopes for complexity values between 3 and 4 were positive and steeper for the EL than LL group, which suggests a greater degree of maneuver component integration for the EL than LL group. This interestingly implies that an intervention offering support for base movements may indirectly support more complex maneuvers. Offering base maneuver support rather than excluding MWUs from complex movements can be very powerful in creating inclusive public and work environments (e.g., permitting interesting/scenic routes rather than carve straightforward alternatives, as is currently often seen). From this finding we conclude that useful cues for base maneuver components may be extracted and applied to new situations with thus less honed motor programs. This result reinforces the assumption proposed above that age-related cognitive decrement minimally impacted the present results- otherwise estimated low performance would have been highly correlated with tasks of high complexity.

Complexity regressions may also be viewed in tandem with the reduced independence in the LL compared to the EL group. The determination of whether reduced independence was attributable to “a lack of need to do the task” or to “a lack of necessary assistance” is not easy since neither the EL nor the LL group reported a greater reliance on assistance than the other. Nevertheless, from the ensemble of results, it may be hypothesized that some barriers (e.g., less time, less practice/training) may have prevented a more wholistic development of motor programs in the LL group that would have otherwise led to more comparable estimations of performance between the two groups. Many short-term gross motor training studies involving older adults utilize training periods ranging from weeks to months; however, despite an approximate 6 years mean experience for LL participants, the predicted performance and independence between EL and LL groups were still significantly different[42]. Therefore, better knowledge regarding the retention of short-term training skill is needed. Investigations examining long-term impacts of wheelchair training are lacking, perhaps due to general challenges in accessibility and scheduling for aging adults with disabilities[40].

3.6.3 Observed trends in MW usage

The Pearson's correlation coefficient between the TD estimated performance and number of anticipated events was r = -0.79, with lower performance correlating with a greater number of assumed events. This expected result supports the use of observed events as a predictor of performance and thus the level of integration of internal representation.

Many results and observed trends add to an overall likelihood that barriers and pain points against the LL group remain invisible. First, Chi-square trends indicate reduced independence in the LL group, yet the LL group did not report greater reliance on assistance than the EL group. Thus, it may be assumed that potential challenges are experienced in everyday activities, but certain scenarios may be avoided altogether. The LL group also reported lower self-efficacy than the EL group. This result was expected given the relatively low estimated performance scores for each maneuver component by the LL group. Motor program training requires repetition, however when self-efficacy is low, then high psychosocial stress and self-limitation of participation have been shown in those with recent incidence of disability[25,128]. Coupled with lower learning capabilities during aging, those with LL incidence of MW usage may be facing great barriers to motor learning[120]. Comments reveal that participants perceive their own relevant sensorimotor limitations. It is possible that while the LL group may not be fully cognizant of their capabilities, they may be keenly aware of the relatively recent reduction thereof. Note that since the recruitment criteria allows us to presume that EL and LL groups were similar in terms of MW propulsion capability (i.e., no spatial neglect, no limitations or alterations in upper extremity, no visual or cognitive impairment) and age, group differences are likely attributable to incidence periods. While we were unable to examine a covariate, outcomes from Chapter 6 suggest that years of experience may be less of key factor than initially expected.

Overall, trends in independence align with statistical findings, and both are encouraging towards our goal of targeting motor planning as a means of supporting MW mobility.

3.7 Conclusion

In conclusion, analyses very strongly support the hypotheses of differing TD estimations of mobility performance between older adults who age into versus with MW usage due to internal task representation (i.e., somatorepresentation, which in turn leads to motor action and program differences). Our results suggest that there are opportunities to provide environmental support to basic elements of maneuver components so as to improve the performance of complex maneuvers. Further, in line with our hypotheses, those with LL incidence of MW usage expressed a greater need for mobility support, thereby indicating the inappropriateness of viewing both incidence period groups (EL, LL) as a single population.

Finally, this exploratory phase informed the outcome measures and environmental conditions to be explored in subsequent studies. The TD prediction of performance $\eta^2 = 0.23$ was used to calculate future target sample sizes using the *simr* package in R Studio. Results showed that to meet a target power of 0.80, a target sample size of 26 total participants would be needed for our future studies (i.e., Chapters 5 and 6). A power analysis for consideration of covariance was not considered, as we anticipated predictor factors to remain dependent in future samples. This may result in reduced generalizability of results and ought to be investigated in future studies beyond the scope of this dissertation. Further, the strong correlation between estimated performance and assumed events supports the use of assumed events as a measure of predicted performance in future studies.

3.8 Broader impact

This survey supports literature findings that (1) aging adults with more recent incidence of disability have reduced self-efficacy and mobility compared to those who have lived with their disability for longer; (2) however, contrary to traditional recruitment methods, within the context of inclusive mobility for constrained environments, the incidence period of mobility limitations ought to be considered; and (3) the number of events and errors committed during maneuvers may be used as a predictor for subjective estimation of performance[21,25,46,55]. These results may be extended to applications concerning design processes, sample recruitment, and as a means to reduce biases in traditional human factors evaluation/usability scales. Further, results indicating reduced independence in public and workspaces for the LL MWUs may be used as a template on where assistive services can be supplemented. In the long term, we assume that inclusive environments will provide greater inclusion with less psychosocial impact compared to the provision of assistance (e.g., wheelchair attendants) as they may also reduce psychosocial impacts currently experienced as a result of poor or lacking of empathy training in public services[49].

3.9 Limitations

As this exploratory study was designed as an online survey, the number of questions and phrasing were limited in order to improve survey completion rates[129]. One study limitation is that lateral tolerances assessed in the maneuvering tasks were fixed values rather than proportional to each participant's occupied width. The fixed values were exaggerated to improve clarity between the two conditions however it should be noted that even in accessibility compliant spaces, situations with narrow tolerances do occur (e.g., blocked hallways, office and dining settings). Narrow constrained movement spaces were described as common by MWUs in open-ended questions and discussions with participants (Chapter 4-6); however, the qualitative aspects of these studies were not the key focus in our prior publications (e.g., Tabattanon et al, 2022)[59,74]. Another limitation is the range of functional capabilities stemming from unscreened medical conditions during recruitment. In the literature, medical conditions are typically controlled in wheelchair research, which results in the investigation of a particular set of functional capabilities[46]. However, since the focus of this research is to examine the impact of incidence period on performance, it was more appropriate to base recruitment on the WHO's ICF; therefore, a large set of functional limitations will be reflected in our participants[24,45]. As participants this survey self-reported no upper extremity prostheses, no upper extremity limitations, and no recent upper extremity injuries (and the capability to independently propel a wheelchair over 7meter distances) the task of wheelchair propulsion is assumed to be consistent between participants and compatible with our aims.

While future work may expand on years of MW experience, the overlap in experience years required would inevitably increase the age of our sample. This may result in unintended changes in participant characteristics. For example, applying an ICF perspective, older participants with EL incidence are anticipated to be more negatively impacted by reduced access to healthcare, which may reduce their overall functional capability beyond the impact of motor skills. Memory and other cognitive decline may also impact older age groups and thus affect task/space representation.

Chapter 4 Influence of Simulated Impairment on Mobility Performance Outcomes

4.1 Abstract

Simulated impairment (SI) is the process of applying a temporary impairment to an otherwise unimpaired subject pool in order to circumvent the need to recruit “hard to reach” populations. It is commonly used in early design processes to determine user needs in lieu of directly engaging a larger pool of stakeholders or in studies investigating physiological functions (e.g., muscular exertion). However, the validity of SI has thus far been only assumed. In this study, 28 manual wheelchair users (MWU) and 43 age- and sex-matched non-wheelchair users undergoing SI were recruited to perform a parallel parking (PP) maneuver. The goal was to determine the minimum PP space needed to perform the task collision-free. Four surface electromyography (sEMG) electrodes were placed on four upper limb dominant-side muscles (bicep, triceps, anterior and posterior deltoids) to analyze muscular exertions. The results show that the depth tolerance required to perform a collision-free PP was significantly greater for the MWU than the SI group. sEMG signals revealed significantly longer biceps exertions for the MWU group, driving main effect differences between groups. Group differences are anticipated to stem from the alteration of sensorimotor processes by chronic MW usage and the disability stress impact on somatorepresentation. This interpretation is in line with unprompted comments from both the MWU and SI groups revealing differences in task perspective and emotional association (i.e., common task vs. new temporary experience; reminder of frustrating or

humiliating experiences vs. fun learning experience). Overall, our findings suggest limited validity in the use of SI with respect to mobility performance measures among older MWUs.

4.2 Introduction

Simulated impairment (SI) is defined as the interactive role-playing experience applied to simulate capability loss or limitations[15]. SI is used, for example, with hopes to bring disability or aging "perspectives" to healthcare training, empathy education, and design or environmental evaluation[15–18]. While mixed results have been reported in education contexts for empathy, findings highlight the unintended consequences such as misattribution of challenges (i.e., "blaming" a health condition as the source of disability as opposed to inaccessible systems), formation of negative or harmful views of people with disabilities, or misplaced confidence that "all" pain points can be experienced through simulated impairment[15,18–20].

SI has been used within early- and late-stage design evaluations of tasks including usability, spatial and/or physiological measures[48–52]. Concerningly, SI has not been validated in the context in which it is used. This sentiment was echoed at the Center for Disability Health and Wellness in October 2022[48]. A September 2023 article in the Journal of Experimental Aging Research from Gerhardy et al.[16] is, to the best of authors' and our knowledge, the first study to examine the validity of age simulation suits (i.e., specialized suits that are commercially available for age-related SI). In their experiment, Gerhardy et al. found a failure to simulate severe functional losses among standardized tests (e.g., Timed Up and Go, grip strength), and 'accurate' simulation of age-related impairments depended on the age of the participant[16]. While disability simulation as opposed to aging simulation is investigated in the present work, the notion that SI has limited validity with regards to significant functional losses supports the hypothesis that non-MWUs may not represent adequately an age-matched MWU population.

4.3 Study aims

The aim of this study was to investigate the validity of SI in its application to accessibility, inclusion, and human factors and design practice. The following hypotheses are tested:

H1) The required minimum parallel parking (PP) clearance is greater for MWU than SI group.

H2) Upper limb muscular exertions are greater for MWU than SI group.

Confirmation of either of these hypotheses would suggest that SI underestimates the needs of MWUs.

4.4 Methods

4.4.1 Participants

Recruitment criteria included:

- Age 50 years or older
- MWU: Use a manual wheelchair (MW) for at least some mobility support
  SI: Do not use a MW
- Able to independently propel a MW for short distances indoors
- No upper extremity prostheses, limitations, or recent injury
- No significant, uncorrected visual, cognitive, or spatial neglect impairment

Participants were recruited through online and paper postings at the Disability Network of Washtenaw, Monroe, and Livingston counties (DNWML), senior communities in the greater Ann Arbor area, University of Michigan (U-M) Health locations such as the geriatric center, Center for Disability Health and Wellness, Turner senior resource center, and the U-M Health

Research website. All participants were screened via either email or phone. A total of 71 participants were recruited. Their characteristics are summarized in Table 4.1.

Table 4.1: Participant characteristic means and counts.

	MWU n = 28		**SI** n = 43	
Age (years)	61.7 (6.3)		59.5 (8.2)	
Sex	F: 19 (67.9%) M: 9 (32.1%)		F: 32 (74.4%) M: 12 (27.9%)	
Handedness	L: 1 (3.6%) R: 27 (96.4%)		L: 4 (9.3%) R: 39 (90.7%)	
Dominant hand grip strength (kg)	20.4 (7.8)		23.6 (7.3)	
Dynamic occupied depth (cm)* ($p < 0.0005$; $d = 0.21$)	109.9 (11.9)		118.0 (3.7)	
Neck range of motion (degrees)	Left ** 60.4 (18.1) ($p < 0.02$; $\eta^2 = 0.08$)	Right *** 56.7 (16.9) ($p < 0.00005$; $\eta^2 = 0.21$)	Left ** 69.5 (12.9)	Right *** 70.1 (9.1)

MWU = Manual wheelchair user SI = Simulated impairment. Standard deviation or percentiles are shown in parentheses, as respectively appropriate. Statistical significance across groups (e.g., Neck range of motion (left) for the MWU group vs. the SI group) is indicated with corresponding series of asterisks (*).

Age, current biological sex (as opposed to sex at birth or current gender), and handedness were self-reported. Grip strength was an average of three dominant-handed trials using a hand dynamometer. Dynamic occupied depths were measured using a standard measuring tape with the participant seated in the wheelchair.

4.4.2 Materials

4.4.2.1 Panels

The PP space were created by standing two cardboard panels parallel to each other and perpendicular to a solid wall. Since contact with obstacles were likely, heavy-duty cardboard was selected as a material to reduce risk of injury or pain in participants affected by lower limb hypersensitivity (e.g., feet nerve damage). Participants in previous studies commented negatively on the use of solid wooden blocks for this reason[74]. To reduce possible discomfort or fear in those with hypersensitivity the experimenters demonstrated that cardboard panels would easily shift in the event of a collision. These panels were weighted at the base with wooden blocks and weights to ensure they remained vertical. Two versions of panels were used (Figure 4.1); the first version utilized pre-existing cardboard panels from a previous study, and the second version utilized new cardboard to replace the older panels after they became dented and bowed from numerous collisions. A thinner design was used to conserve limited material however, this prevented the use of paint on the second version. The panel version did not significantly affect the outcome measure ($p = 0.66$), as indicated in the Limitations section.

Figure 4.1: A MWU participant maneuvering into the parallel parking space. A cardboard panel is seen on either side of the space. (Left) First version, utilizing pre-existing panels; (Right) Second version, utilizing new, narrower panels.

4.4.2.2 Manual wheelchair

A manual wheelchair (70cm x 110cm footprint) was provided for all 43 SI participants and 15 of the 28 MWU participants who requested its use (e.g., they did not own a device and relied on devices provided by public spaces; preferring to use our device rather than traveling with their own). No wheelchair transfer was permitted due to health and safety precautions.

4.4.2.3 Other

A video camera was set-up perpendicular to the blocks, as illustrated by Figure 4.1, to allow for playback and analysis of strategy. At least one experimenter observed from this location to note collisions. Four surface electromyography (sEMG) electrodes (Delsys^{TM} Trigno) were placed on the participant’s dominant arm bicep, triceps, anterior deltoid, and posterior deltoid. The selected muscles are relevant to MW propulsion in several propulsion techniques[109]. Skin was prepped with hypoallergenic sanitization wipes and preparation gel (NuPrep™) to reduce impedance. sEMG data was collected at 2148Hz with the Delsys™ EMGAcquisition software installed on a lab laptop computer.

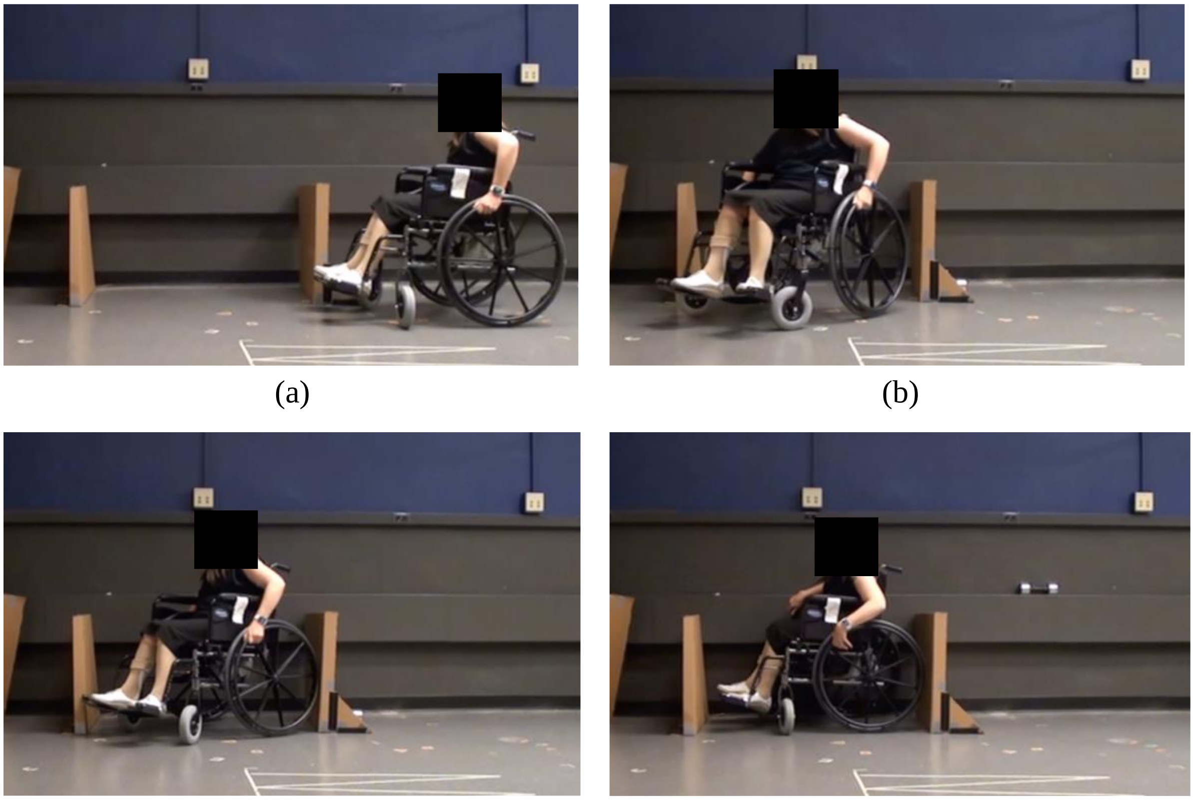
4.4.3 Procedure

The study was approved by the U-M Institutional Review Board. Informed consent was received for all participants. Age and current biological sex were self-reported. Dominant hand grip strength was measured via a hand dynamometer. Occupied dynamic depth in a MW was measured by an experimenter while the participant, seated in the MW, adopted a self-selected posture for comfortable movement. sEMG electrodes were placed on muscles while participants assumed a self-selected propulsion posture. A few test propulsions (i.e., in open space, not within the PP space) were observed by the experimenter to ensure the electrode alignment with the muscles during movement.

After electrode placement, maximum voluntary exertions (MVE) sEMG signals were collected for each muscle using the corresponding resistive maneuvers. For three MWU participants, MVEs were collected in the forward propulsion dynamic posture. The intent was to match the length tension of the muscles and gain a representative impression of task-specific muscular exertion. For this, the participants self-selected their hand position on the hand rim. However, due to the dynamic nature of the PP and subsequent adaptations, joint angles were later discovered to differ significantly from the MVE posture. This was evidenced by an underestimation of MVE and >100%MVE muscular exertion for these MWUs, particularly in the anterior and posterior deltoid muscles (trials exceeding 100%MVE were excluded from final analyses). Therefore, the MVEs for all remaining participants were collected with the elbow at 90° flexion and the shoulder at 0° abduction and flexion, forearm not resting on the armrest. The MVE corresponded to the highest of two 3-second trials separated by adequate rest periods.

Then, two parallel blocks were set at a distance of the participant’s occupied depth plus 5cm. This was done avoiding participant field of view so they would now know how much initial clearance was allotted. Hence, unaware of the clearance, the participants had to rely on their internal representation of their occupied space and maneuverability.

Participants were then shown the PP space. A starting point was indicated slightly to the left and behind one of the blocks. Instruction was given to move in between the blocks, in whichever maneuver was preferred, such that the ending position was squarely within the blocks defined space and face the same direction the maneuver started from (Figure 4.2). The instructions emphasized at least twice that time was not limited, speed was not a priority, and any maneuver may be used. The trial with an increased 2cm clearance was repeated if any collisions were noted by the observer. The clearance wherein no collisions were committed was recorded as the minimum PP clearance.



(a) (b)

(c) (d)

Figure 4.2: Typical example of the four stages of the parallel parking task. A MWU participant is seen (a) starting the task, (b) moving in a self-selected maneuver into the parallel parking space, (c) colliding with the back panel, (d) finishing fulling in the space. Since collisions occurred, a subsequent trial was needed for this participant.

PP practice was not permitted before the test trials. However, a five-minute practice period of MW movements in the large laboratory open space was provided. Both MWU and SI participants stated that they were envisioning the parallel blocks as they practiced in open space. All participants requested to perform the test task before the end of practice time.

4.4.4 Analysis

The minimum clearance required to perform a collision-free PP was compared between the MWU and SI groups using a one-way ANOVA. The "*stats"* package in R studio was used for the data analysis. All raw sEMG signals, including the MVE trials, were band passed filtered by a 2nd order Butterworth 10-500Hz, then the RMS signal was computed using 0.25sec windows with 0.0625sec window overlap. Muscular exertion was defined as a percentage of MVE (%MVE). RMS signals were normalized using the respective muscle MVE signal, and histogram distributions for exertion levels were generated. Histograms bins were categorized by muscular exertion: Low (0-10%MVE], Moderate (10-40%], High (40-80%MVE], Extremely High (80-100%MVE].

4.5 Results

4.5.1 Minimum required PP clearance

The grip strength (kg) was not significantly different ($p > 0.2$) between the MWU and SI groups. The grip strength covariate was not significant ($p = 0.5$); the interaction between groups and grip strength was also not significant.

The parking space clearance required by the MWU group was 8.9 (5.6)cm and 7.0 (2.4)cm for the SI group (Figure 4.3). The 95th percentile confidence interval for the MWU and SI are 2.2 and 0.8, respectively. Minimum clearance means are statistically different between MWU and SI groups ($p < 0.05$), with $\eta^2 = 0.08$.

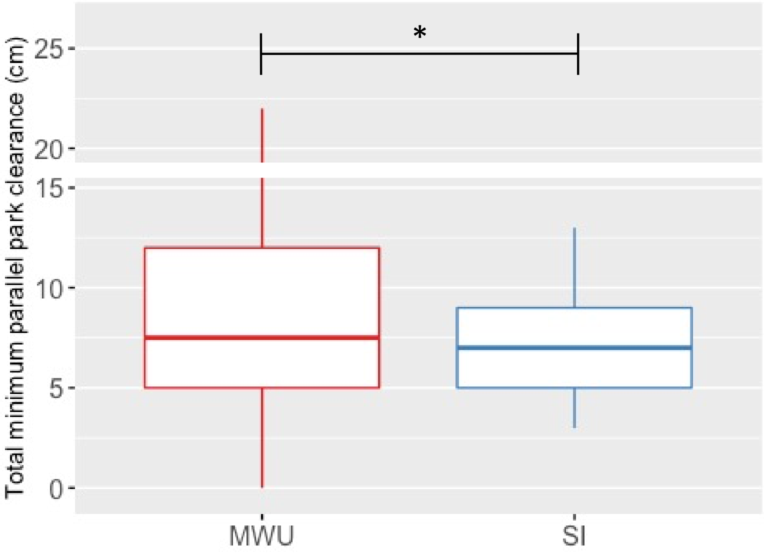


Figure 4.3: Minimum clearances required by the MWU and SI groups to perform the parallel park task without collision.

4.5.2 Muscular exertion

Exertion levels were less than 40%MVE. Figure 4.4 depicts the boxplot for all Moderate %MVE exertions by muscle and group; as only two histogram bins contained data points (i.e., Low and Moderate exertion), only the Moderate bins are illustrated as the Low bins are simply complementary by definition.

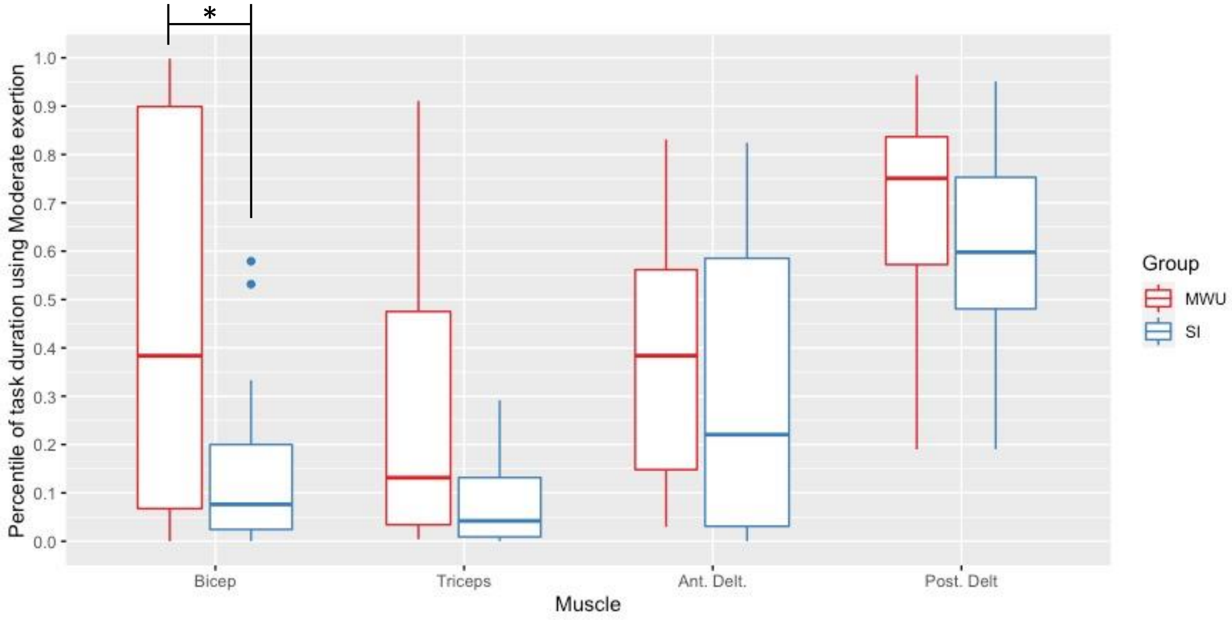


Figure 4.4: Percentile of moderate muscular exertion during the parallel parking task.
Note: The sum of Moderate and Low percentiles (not shown) equal 100% exertion profile for each muscle.

The ANOVA showed a significant group effect ($p < 0.0005$) indicating that Moderate muscle contractions were longer for the MWU than the SI group. Inter-muscles comparisons (e.g., bicep exertion vs anterior deltoid exertion) were not tested, as not relevant. The interaction of muscle and group yielded only one significant difference with the mean Moderate bicep exertion percentile higher for the MWU than the SI group ($p < 0.005$). Hence, the group difference is assumed to be largely based on a significantly longer biceps exertion by the MWUs than the SIs.

4.6 Discussion

4.6.1 Minimum required PP clearance

Although mean clearance values presented some similarity, the range of values was lower for the SI than the MWU. This implies that SI can potentially bias environment space measures commonly considered appropriate for disability simulation and ensuing applications. Tasks under this assumption often include "purely physical" endeavors that may be practiced, as exemplified by the parallel parking task. Thus, the use of SI may falsely lead designers or researchers to overlook the true "5th to 95th percentile" range of the population being simulated. Estimations or models based on data collected from SI may also not accurately reflect the MWU population without further research and advanced anthropometric databases. Hence, our results suggest that the validity of SI may be less than popular assumptions[50,130]. Therefore, recruitment of disability populations directly, despite being "hard to reach", would better reflect inclusion and more accurately represent the needs of target users. In time, such populations may be less difficult to access as systems and environments become more inclusive.

Our MWU and SI samples used significantly different dynamic occupied depths. The type of MWs owned and thus used by participants was not controlled for this study. This was due to health and safety reasons (e.g., personnel training for a range of transfers; prolonged close contact with participants that conflicted with COVID-19 precautions). While it may be speculated that MW type could affect results, we assume that our conclusions with regards to MW SI holds in validity for the following reasons:

1. *Both user groups used our lab MW.* While some participants in the MWU group did arrive in their own device, 15 of 28 (53.6%) used the same MW as the SI participants. Hence, the performance of the SI group does not appear as strongly dependent on wheelchair type.
2. *Smaller MW depth, larger clearance.* The occupied depth was smaller for the MWU than the SI group. Intuitively, one would expect smaller devices to bias results towards smaller required clearances. This, however, was not the case, suggesting that this characteristic may not have had a significant influence. On the contrary, this is in support

of a degradation of MWU sensorimotor abilities when compared to the age-matched SI group, as emphasized below.

3. More custom MW, larger clearance. The smaller MWs used by the MWU group were also more customed than the standard MW offered by the study. Intuitively, one would expect these custom devices to have tighter turn radii and higher maneuverability than a standard MW. Although our study did not collect the model of each personal device, several MWU participants stated that their device was lightweight and of high maneuverability. Yet our results suggest that maneuvering was more refined/precise for the SI compared to the MWU group. This means that space perception and/or motor skills differ between MWU and SI group. It may be inferred that the integration of sensorimotor information was affected by disability, as will be discussed in terms of somatoperception and somatorepresentation.

It is hence assumed the enlarged PP clearance needed by the MWU group is most likely due to differences in sensory-motor abilities rather than an effect related to the mobility aid. However, as lived experiences impact underlying motor control processes, we propose that beyond differences in motor skills, chronic stress and engrained emotional associations impact somatosensory processes. This mind-body monism was originally proposed by the philosopher Spinoza in the 17th century and proposes that emotions (within the prefrontal cortex) influence motor control (within the somatosensory cortex). The corresponding mechanism is supported by modern understandings of somatorepresentation and neuroscience[131,132].

4.6.1.1 Direct motor control contributions to group differences

Mobility limitation contributes to a decrement of proprioceptive information and muscle control, which would subsequently lead to motor control alteration (e.g., limb immobilization, loss of muscle mass in certain areas/gains in others)[83,88]. Here, somatoperception and somatorepresentation, is suspected to differ between groups. Specifically, the disuse of a limb (e.g., the legs in the case of manual wheelchair usage) leads to recruitment of other muscles (e.g., the arms for wheelchair propulsion), and use of newly recruited muscles and/or tools (e.g., hand tools, mobility aids) leads to an extension of body representation to encompass the tool as it is being used in the newly appointed limb[88]. Effectively, this phenomenon results in altered somatorepresentation of the body. On the other hand, disused muscles face subsequent reductions in mass, fibers, and neuromuscular control which in turn lead to a loss of proprioceptors and thus reduced proprioceptive capabilities, limiting somatoperception[83,90]. In sum, internal body representation is expected to differ between MWUs and SIs.

4.6.1.2 Indirect motor control contributions to group differences

Chronic stress induced by a physical disability likely influences motor behavior through the interference of sensorimotor processes(see for review Longo et al., 2010), as well as long-term motor learning[83,133–135]. Negative emotions and stress about the body results in disproportionate representation of body size, for example in people who experience eat disorders[83,92]. MWUs may experience a similar phenomenon resulting from the prolonged psychosocial stress associated with usage of a MW. This reasoning is supported by comments from MWUs indicating they have experienced tight maneuvering spaces in public (e.g., transit, bathrooms) compared to comments from SI that they “doubted” MWUs experience such small spaces at all.

Viewing disability by the ICF framework, these results suggest that factors other than the MW are impacting the outcome measure. Hence, it is postulated that the MWU’s performance is more influenced by lived experiences, trained motor programs, self-efficacy, and sensorimotor capability rather than MW design. Therefore, simulation of wheelchair maneuvers by non-MWU individuals may not be representative.

4.7 Muscular exertion

The significant main effect MWU vs SI muscular exertion was primarily driven by the bicep muscle, suggesting that SI validity is not present in contexts where sEMG measures represent motor patterns associated with maneuverability. Moderate bicep exertion is of greater magnitude and more prolonged for the MWU than the SI group (see Figure 4.4). This indicates that the MWU would fatigue faster than the SI for the same task and correlates with group differences in the neck range of motion. Specifically, due to a smaller range of motion for the MWU than the SI group, greater corrective maneuvers are anticipated since rearward visibility is consequently limited. For such corrective maneuvers, the observed bicep exertion suggests greater postural strain and small/precise movements are being made by the MWU group. These results support the hypothesis that SI may overlook underlying group differences in sensorimotor processes, such as reduced confidence from somatoperception impacted by reduced range of motion; or increased postural strain from somatorepresentation impacted by the desire to reduce errors made in public[16,136]. This latter point alludes to the emotional differences between groups where the MWUs expressed that those tight spaces were reminiscent of stressful situations while the SIs had no similar reaction.

Overall, the sEMG results suggest that the use of SI would disallow researchers from examining the true range of outcomes. In terms of design or environmental outcomes, SI may lead to insufficient accommodations and an inaccurate understanding of the range of users within the population.

4.7.1 Parallels from disability studies literature

Our qualitative findings support disability studies literature with respect to empathy outcomes from SI and its surrounding controversy[19,137]. Specifically, results suggest that SI participants understood the temporary nature of the simulation and thus viewed ambulation from self-centered lenses[20]. Multiple SI participants freely expressed their thoughts before, during, and after performing the PP task. Sentiments included expectations of performing "worse" compared to "real MWUs"; general frustration at the simulation (one stated, "this is not fun", and considered withdrawing directly as a result); feeling "grateful" or "appreciative" for not needing a wheelchair in their "real life"; and doubting whether lateral movement was reflective of real-life maneuvers that MWUs actually encountered. In contrast, multiple MWU participants reflected on times they have had to perform lateral movements or maneuver into a tight space with very little clearance (e.g., on public transportation, moving as close to a wall as possible; in dining or office settings). MWU participants also mused about the benefits of using highly maneuverable MWs; however, not all owned such a device (e.g., due to cost, insurance limitations). One MWU stated that while they did own a highly maneuverable device, they were not always able to use it due limits in transportation or having "good and bad" days.

Such subjective differences between actual users and the simulated group has the potential to impact design and designer *attitudes* towards inclusion since the ideation process can face numerous pitfalls, such as (1) leaning towards accessibility patches that support participation rather than inclusive systems that support equity, (2) misplaced confidence that stakeholders are not needed in early design processes, (3) considering "able-bodied" capabilities, in this case ambulation, as a "norm"/the "normal way" to complete a task[48,130]. While an examination of the behavioral and psychological impact of SI is beyond the scope of this study, we note the importance for designers and researchers alike to understand and consider these aspects when addressing issues of inclusion.

4.8 Conclusion

We utilized a maneuvering task consisting of all base movement components (i.e., forwards and rearwards propulsion, left and right turns) to compare the maneuverability and sEMG signals for older MWUs to age- and sex-matched SI users. The results of this study suggest very limited validity of SI in measures relating to maneuverability. This contrasts with what has been commonly assumed in practice. SI consistently exhibited a narrow range of results when compared to the large variability characterizing the population of MWUs. Such differences show that simulation may bias results and effectively “spotlight” an arbitrary range of performance within the true target population’s capabilities. Our findings support the active recruitment of disability populations for human factors evaluations and research since task representation and sensorimotor abilities do not equate between MWUs and SI individuals.

4.8.1 Broader impact and recommendations

Results may be applied to universal and inclusive design practice by highlighting potential invalidity in using SI. SI is very commonly assumed to be valid without context-specific validation. While the reasoning behind SI is understandable (e.g., budgetary constraints for recruitment), researchers must understand the limitations of result generalizability. From our findings, we recommend the direct recruitment of older MWUs when outcome measures relate to or rely upon maneuverability or muscular exertion as SI may bias results.

4.8.2 Limitations

Two versions of the cardboard panels were used to set up the PP space (one with and one without a grey paint finish). This may have biased spatial perception and motor planning. However, we believe color had a minimal impact on the findings for the following reasons: (1) both colors were in good contrast with the immediate environment; (2) all participants were given time to practice maneuvering in the open space near the PP set-up; (3) all participants were permitted to view the space from different angles in their practice, and the experimenter physically entered (via ambulation, not in a wheelchair) the space while demonstrating the task. All reasons gave participants the opportunity to evaluate the space with a size reference (i.e., the experimenter). In addition, analysis of participants who experienced either version of the panels yielded similar findings ($p = 0.66$).

Although physical disability may have differed between MWUs, the applied selection criteria were sufficient to prevent these disabilities from directly interfering with MW maneuvers. However, as discussed, indirect effects may have contributed to some extent in results variability. Yet this variability is rather a positive outcome supporting our claim that simulated impairment is not appropriate to infer inclusive design.

Participants in both the SI and MWU group noted the similarity between the task and a vehicular parallel park; in future iterations of this study, a questionnaire regarding driving experience and skill may be included. And further, while this finding casts suspicion upon the use of simulated impairment in examinations of strength and ease of maneuverability in wheelchairs, the present study did not specifically investigate measures of strength or situations of high exertion (e.g., ramp inclines that rely largely upon shoulder exertion)[50,130].

Chapter 5 Influence of Augmented Visuospatial Interventions on Path-Following Performance for Aging Manual Wheelchair Users

5.1 Abstract

The aim of this study was to investigate the effects of environmental visuospatial feedback interventions on path-following performance for aging manual wheelchair users (MWUs). A total of 26 MWUs aged ≥ 50years were recruited. The task consisted of following a path containing a 6m straight section with walls constructed from heavy-duty cardboard. A Baseline condition with indications on nether the floor nor walls was followed by intervention conditions utilizing one top-down (TD) and two bottom-up (BU) augmented visuospatial information. The TD intervention was a sign that depicted the lateral tolerance within the path; the BU interventions consisted of (1) a continuous midline marker on the floor along the length of the path and (2) a set of four transverse rulers with 2cm lines along its length spaced by three equidistant intervals along the path. Four sEMG sensors were placed on the dominant bicep, triceps, and anterior and posterior deltoid, respectively. The TD intervention successfully supported a more accurate internal representation of the navigation space; while the BU interventions successfully provided enhanced visuospatial feedback that supported (1) movement perception within the constrained path and (2) internal integration of spatial information and dynamic occupied footprint. Interestingly, the transverse rulers seem most effective in supplying the somatosensory and motor processes with the spatial information required to adjust

movement. The sEMG results suggest elevated postural tension due to the increased awareness of space during the TD intervention. In sum, simple TD and BU interventions appear to positively assist wheelchair navigation and thus could favor mobility inclusion, which may be greatly beneficial in unfamiliar, constrained environments.

5.2 Introduction

Mobility during older age is critical for healthy, independent, and successful aging[27,28]. However, mobility has become discriminatory with inadequate accessibility within built environments, including places of work[12,31]. Manual wheelchairs (MW) have become increasingly relied upon by aging adults to support mobility loss, such that older adults are currently the largest user age group[34,35]. Yet, without the appropriate navigation space, movement can be unsafe or very challenging[138]. The same is true for ambulation, however populations with mobility disability are often left behind[49,59]. In fact, inadequate mobility independence in the face of disability reduces one's independence and quality of life, and thus leads over 22% of older adults to depend on others with increasingly reliance on unpaid services (e.g., family)[29,30]. It is crucial to note that even temporary obstacles that require wheelchair users to ask for assistance can significantly reduce their inclusion and sense of belonging[25,139].

5.2.1 Motor action

Human motor control and resulting actions are derived from internal motor planning and sensorimotor feedback systems[79]. This process, applied to MW movement, is summarized in Figure 5.1.

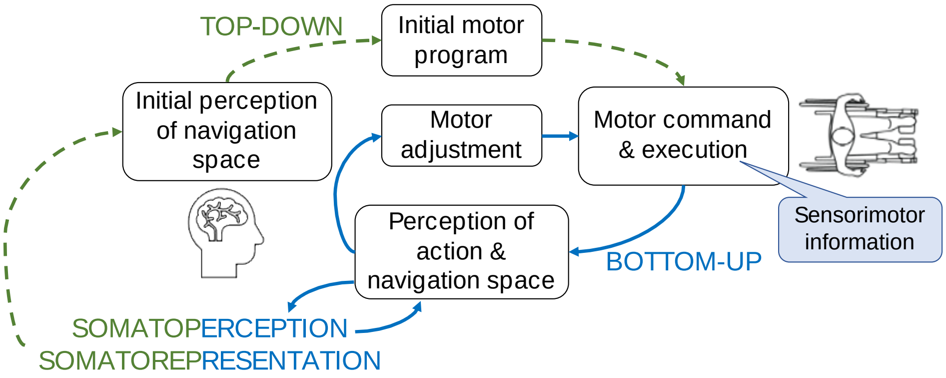


Figure 5.1: The motor planning, action, and correction loop

Motor planning is driven primarily by TD perceptions of our body and the environment[80]. Somatosensory processes inform motor program adjustments, for example drawing in goal-directed sensory cues[94–96]. Within these processes, somatoperception symbolizes information about the body (i.e., size, location, shape) and objects in contact with the body (in this case, the MW)[83,88,89] It allows motor programs to account for body and posture then account for potential contact with other objects[83]. Whereas somatorepresentation is the recognition of what one's body is believed to be like, based on knowledge and beliefs about it[83,88]. Somatorepresentation allows motor programs to take into account psychosocial factors, emotions, and knowledge about how the body can move/exist in association with different movements[83].

Following motor command and initial execution, BU sensorimotor feedback (e.g., visual, proprioceptive) provide the information necessary for motor adjustment towards meeting a movement goal[81,82]. As with TD planning, somatoperception and somatorepresentation inform motor adjustments. Within the environment, attentional cues and stimuli provide information regarding how the executed movement compared to our internal goal. The provision of such cues (e.g., clearly marked lanes on a road) can support movement.

5.3 Study aims

The aim of this study was to investigate the effects of TD and BU environmental interventions on path-following performance for older MWUs. The following hypotheses were tested:

> **H1**) The number of collisions committed within a path-following task will be reduced by augmented visuospatial information, when compared to baseline (i.e., no intervention). This effect will be greater for BU than TD intervention conditions.
>
> **H2**) The subjective ratings of assumed frustration and perceived frustration will be more congruent for environmental intervention than baseline conditions.
>
> **H3**) Dominant side muscle activity (via sEMG) will be lower in environmental intervention conditions than baseline (i.e., no intervention), as movement uncertainty will be reduced. This effect will be stronger for BU than TD interventions.

5.4 Methods

5.4.1 Participants

Participants were recruited through online and paper postings at the Disability Network of Washtenaw, Monroe, and Livingston (DNWML, formerly the Ann Arbor Center for Independent Living), senior communities in the greater Ann Arbor area, University of Michigan (U-M) Health locations such as the geriatric center, Center for Disability Health and Wellness, Turner senior resource center, and the U-M Health Research website. All participants were screened via either email or phone and scheduled for one 2hour experiment session (both Baseline and Intervention studies were 2hours duration).

Participants were recruited with the following criteria:

- Age 50 years or older
- Used a manual wheelchair for at least some mobility support
- Able to independently propel a manual wheelchair for short distances indoors
- No upper extremity prostheses, limitations, or recent injury
- No significant, uncorrected visual, cognitive, or spatial neglect impairment

A total of 26 older adult wheelchair user participants were recruited. Table 5.1 summarizes their characteristics from both the baseline and intervention studies.

Table 5.1: Summary of participants.

	Baseline study n = 15		**Intervention study** n = 13	
Age (years)	62.4 (6.7)		60.8 (6.7)	
Sex	Female: 10 (66.7%) Male: 5 (33.3%)		Female: 9 (69.2%) Male: 4 (30.8%)	
Dominant handed grip strength (kg)	21.8 (8.0)		18.8 (7.9)	
Dynamic occupied width (cm)	76.5 (6.6)		74.7 (5.4)	
Neck range of motion (degrees)	Left 63.5 (17.6)	Right 58.1 (14.0)	Left 56.9 (18.7)	Right 55.2 (20.3)

Standard deviation or percentiles are shown in parentheses, as respectively appropriate. No statistical differences were found for any demographics and anthropometry measures.

Age and current biological sex (as opposed to current sex or gender) were self-reported. Grip strength was obtained as an average of three dominant-handed trials using a hand dynamometer. The dynamic occupied width was measured using an anthropometry caliper with the participant seated in the wheelchair, assuming a propelling posture with the widest width as determined through visual observation. Width was measured knuckle-to-knuckle as this was the widest distance within the height of the cardboard panels. A goniometer measured the neck range of motion while the participant remained seated in the wheelchair. Participant characteristics were not significantly different between the Baseline and the Intervention study.

5.4.2 Materials

5.4.2.1 Panels

An adjustable path-following task was constructed using heavy-duty cardboard panels (Figure 5.2). The path is 7m in length, with 6m of straight path and 1m right angle turn. Panels were either secured to the floor or weighted to prevent horizontal displacement from collisions. Since contact with obstacles were likely, heavy-duty cardboard was selected as a material to reduce risk of injury or pain in participants affected by lower limb hypersensitivity (e.g., nerve damage in their feet). Participants in previous studies commented negatively on the use of solid wooden blocks for this reason[74]. The experimenters demonstrated to the participants that the cardboard panels would easily shift in the event of a collision; this was done to further reduce any discomfort or fear in those with hypersensitivity. Panel tolerance was determined utilizing the occupied dynamic width at the widest points below the height of the panels; it was assumed that measuring occupied width at the elbows would result in tasks that were "too easy" to provide meaningful results. On the other hand, taller panels were not utilized to limit the possibility of claustrophobic emotions. The path used physically resembles furnished spaces as reduced to a narrow hallway as both are known to have similar floor-footprint constraints. The "Start" and "End" lines of the path-following task were clearly marked by striped yellow and black tape.

Figure 5.2: Illustration of the path-following task. One experimenter observes critical event counts while the other monitors sEMG signals to ensure safe levels of muscular exertion. The image on the left shows no intervention, and the image on the right depicts the “Mid-line marker” bottom-up intervention.

5.4.2.2 Manual wheelchair

A MW was provided to 8 of 15 baseline participants, and 7 of 13 intervention participants requested its use (e.g., they did not own a device and relied on devices provided by public spaces; preferred to use our device rather than traveling with their own). No chair transfer was permitted due to health and safety precautions.

5.4.2.3 Other

Two video cameras were set-up perpendicular to either ends of the path, as in Figure 5.2, to allow for playback and analysis of strategy. At least one experimenter observed movements to provide critical event counts. If this was not possible, critical events were tallied in video playback. Four surface electromyography (sEMG) electrodes (Delsys^{TM} Trigno) were placed on the participant’s dominant arm (upon their bicep, triceps, anterior deltoid, and posterior deltoid). The selected muscles are relevant to MW propulsion in several propulsion techniques[109]. Skin was prepped with hypoallergenic sanitization wipes and preparation gel (NuPrep^{TM}) to reduce impedance. sEMG data was recorded at a frequency 2148Hz with the Delsys^{TM} EMGAcquisition software installed on a lab laptop computer.

5.4.3 Procedure

Both baseline and intervention studies were approved by the U-M Institutional Review Board. Informed consent was received for all participants.

5.4.3.1 Baseline condition

Following informed consent, age and current biological sex were self-reported and dominant hand grip strength measured. The occupied width was measured while the participant, seated in the MW, adopted a self-selected posture for comfortable movement. The experimenters observed a few test propulsions (i.e., in open space, not within the cardboard path) to ensure (1) the widest widths were captured and (2) the electrode alignment with the muscles during movement. sEMG placement on muscles occurred following skin prep and while participants assumed a self-selected propulsion posture. Neck range of motion was measured with a goniometer while the participant remained comfortably seated in the wheelchair at rest.

Then maximum voluntary exertions (MVE) sEMG signals were collected for each muscle using corresponding resistive maneuvers. For three MWU participants, MVEs were collected in the forward propulsion dynamic posture. The intent was to match the length tension of the muscles and gain a representative impression of task-specific muscular exertion. However, adaptive strategies adopted by some participants led to us changing the MVE posture to static postures. Therefore, the remaining participant MVEs were collected with the elbow at 90° flexion and the shoulders at 0° abduction and flexion, forearm not resting on the armrest. The MVE corresponded to the higher of two 3-second trials separated by adequate rest periods.

During MVE rest breaks, experimenters set up the path-following task path panels. Participants were informed of neither the measurements nor tolerances used. This was done to conceal the allotted tolerance from the participants, ensuring they had to rely on their internal representation of their occupied space and maneuverability.

The participants were then directed to the Start position behind the corresponding black and yellow tape. The task consisted in moving in a forwards-direction towards a dominant-handed turn within the path with a lateral tolerance of 5cm and of 8cm. Three trials were completed. It was required to maneuver through the path "as quickly as possible while prioritizing safety". The participants were also instructed to "imagine the cardboard walls were tall concrete walls", hence "consider avoiding collisions as a part of safety". These instructions were repeated at least once to avoid confusion.

Prior to each Trial 1, a questionnaire regarding the assumed performance (i.e., how participants *predicted* they would perform) was completed. The questions are summarized in Table 5.2.

Table 5.2: Summary of assumed performance questionnaire

Question	**Response type**
Do you expect you can complete this task without requesting assistance?	Binary: Yes / No
Frustration	NASA TLX [0,20]
Comments	Open-ended

NASA TLX: NASA Task Load Index[112]

Collisions were counted by one experimenter while the other monitored the sEMG signals (see Figure 5.2). Following Trial 3, a questionnaire regarding the perceived performance (i.e., how participants *felt* they performed) was also completed. The questions are summarized in Table 5.3.

Table 5.3: Summary of perceived performance questionnaire.

Question	**Response type**
How was the perceived difficulty of the [task]?	EUM [1,7]
Performance	NASA TLX [0,20]
Frustration	NASA TLX [0,20]
Comments	Open-ended

NASA TLX: NASA Task Load Index; EUM: Environment Utility Measure[112,115].

Then a series of post-trial questions were asked concerning the MW usage and frequency of use, challenges experienced, and interventions that may be helpful in movement. Comments regarding general health and upper extremity usage were also collected.

5.4.3.2 Intervention conditions

The same procedure was used for each condition. However, a few questions were added to the post-trial questionnaire:

1. If you [completed the Baseline condition], did the tasks feel different [with interventions]? Did any changes impact your level of confidence in your performance or in your responses before / after each task?
2. Did you think the markers and sign helped your performance? Why/ why not?

Three interventions were designed to facilitate navigation and movement within the constrained environment: One TD intervention and two BU interventions. All interventions were intended to provide augmented visuospatial information. As auditory or tactile capabilities were not screened, interventions were limited to the visual mode. The intervention order was balanced in a mixed design. Each participant completed four conditions with three trials per condition. Only forwards-direction, dominant-handed turns at 5cm and 8cm lateral tolerances were tested.

Top-down intervention: Sign. Signs were designed to support manual wheelchair's initial perception of space and thus motor planning. To-scale illustrations of space were printed and placed on cardboard cut-outs, as reproduced in Figure 5.3. The signs were stored face-down so the participants were not aware of tolerance levels until the intervention was revealed. Each element of the sign was read aloud to the participant prior completion of the Assumed Performance Questionnaire before Trial 1. Henceforth, this intervention is referred to as "TD Sign".

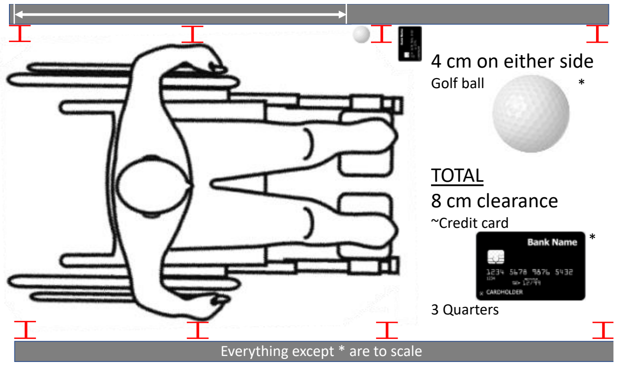
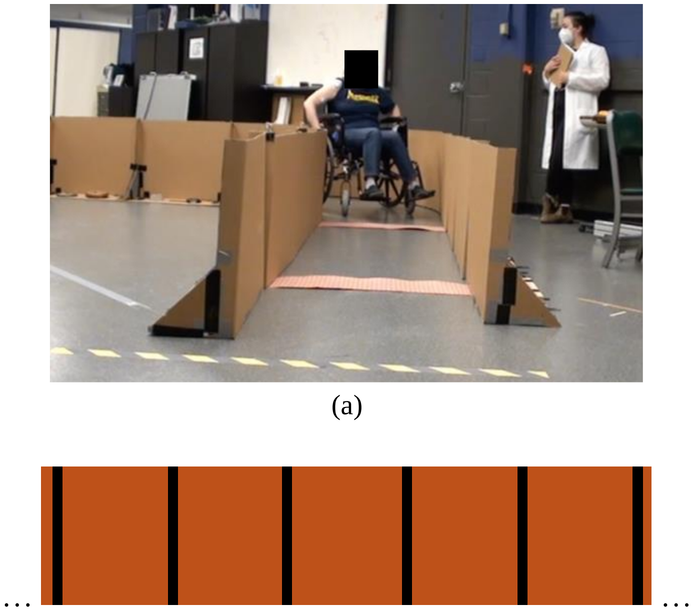


Figure 5.3: The top-down intervention for the 8cm total clearance lateral tolerance.

Bottom-up intervention 1: Midline marker. A salient yellow yarn was taped to the floor along the straight segments of the path-following task (see Figure 5.2**,** Right side). As path widths are determined by the occupied dynamic width, the mid-line was visually estimated and confirmed by experimenters. Henceforth, this intervention is referred to as “BU Midline”.

Bottom-up intervention 2: Traverse rulers. Thick, black lines were drawn 2cm apart across the length of four strips of heavy paper (Figure 5.4) placed along the path. The edges of the paper were secured underneath the cardboard panels (i.e., path walls) at the ends and the path and prior to the corners. The participants were informed that the lines were spaced 2cm or “approximately one inch” apart. Henceforth, this intervention is referred to as “BU Ruler”.



(a)

(b)

Figure 5.4: (a) The BU Ruler intervention, with the heavy paper strips secured on the floor using the cardboard panels forming the walls. (b) A short sample depicting the ruler marks spaced 2cm apart over the length of the ruler.

5.4.4 Analysis

Critical events are compared between studies using an ANOVA across Baseline and Intervention conditions. Ratings of assumed and perceived performance were compared across all conditions. As the interventions were only applied to the straight portions of the path, only collisions along these sections were compared. To reduce inflation of Type I errors, only the lateral tolerance of 8cm is examined. This decision was made as the 8cm tolerance was the "middling" difficulty tolerance. Comparisons for the 5cm tolerance were likely to yield misleading results as the narrow tolerance was rated as highly difficulty by all users in the exploratory survey (Chapter 3). Pearson's correlations were used to examine collision counts relative to subjective ratings (i.e., frustration, performance, difficulty). The difference between assumed and perceived frustration is examined via percentage difference. The "*stats"* package in

R studio was used for the data analysis. Qualitative comments were considered towards a mixed methods understanding of performance results.

All raw sEMG signals, including the MVE trials, were band passed filtered by a 2nd order Butterworth 10-500Hz, then the RMS signal was computed using 0.25sec windows with 0.0625sec window overlap. Muscular exertion was defined as a percentage of MVE (%MVE). RMS signals were normalized using the respective muscle MVE signals, and histogram distributions for exertion levels were generated. Histograms bins were categorized by muscular exertion: Low (0-10%MVE], Moderate (10-40%], High (40-80%MVE], Extremely High (80-100%MVE].

5.5 Results

5.5.1 Critical events

Critical events observed included resting, withdrawing from fatigue, and collisions with the wall panels. Two participants stopped to rest in the middle of the path during the Baseline condition. One participant withdrew from fatigue during their second Baseline trial. No other during-trial rests or withdrawals occurred. Thus, only collisions were statistically examined.

The numbers of collisions committed are summarized in Figure 5.5. Collisions were significantly fewer in the presence of the BU Ruler than in the Baseline condition ($p < 0.02$). The BU Midline condition appeared marginally effective but was not significant when compared to baseline ($p = 0.067$). No other significance was observed.

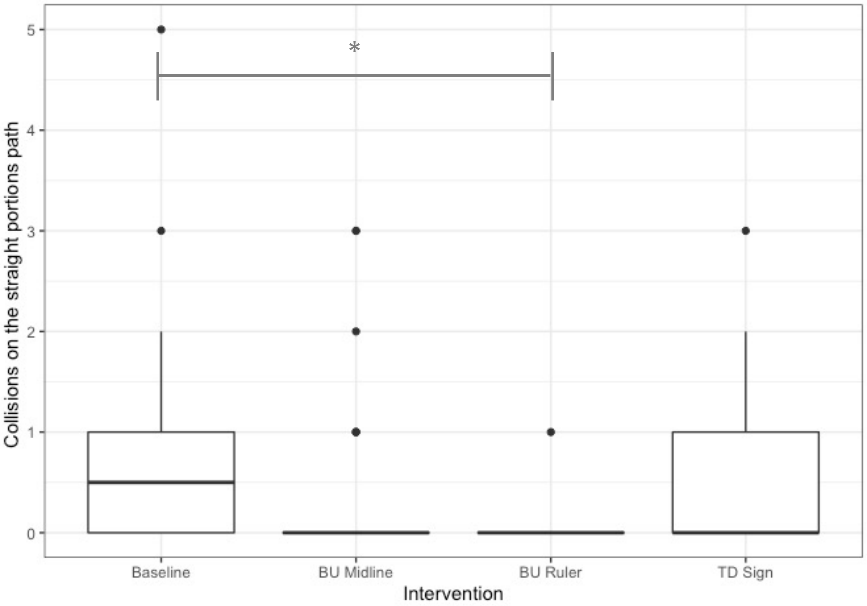


Figure 5.5: Collisions committed along the straight portions of path. *BU: Bottom-up intervention; TD: Top-down intervention*

Verbally, participants commonly reported collisions with their hands with the walls (e.g., ‘That would have really hurt if that was a real wall’), watches or rings with the wall (e.g., ‘I would take it off to avoid damaging it’), and the wheelchair with the wall (e.g., ‘The walls in my home are marked where I hit the wall [like that]!’).

5.5.2 Subjective ratings

Frustration, performance, and difficulty ratings are reported in Figure 5.6. Frustration ratings were collected both before Trial 1 and after Trial 3. Performance and difficulty were only assessed after Trial 3.

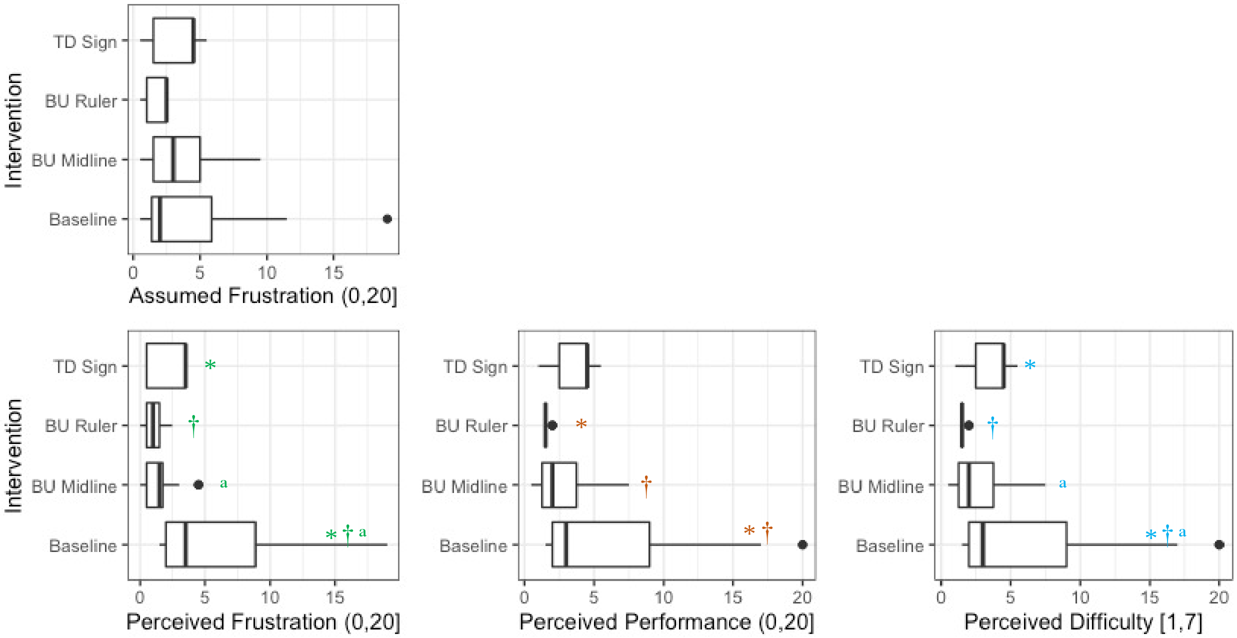


Figure 5.6: Summary of the respective subjective ratings. Statistical significance between the intervention types is indicated with corresponding superscripts. All p-values marked significant are $p < 0.0006$. *Note: Interactions between rating types were not accessed. Assumed ratings occurred prior to Trial 1; Perceived ratings occurred following Trial 3.*

Correlations between collisions and subjective ratings are summarized in Table 5.4. Positive r coefficient values indicate higher subjective ratings (defined in the table) correlating to a greater number of collisions. For example, in the BU Midline intervention, a greater perceived frustration correlates to a higher number of collisions. On the other hand, negative r coefficient values indicate a higher rating with a lower number of collisions. Foe example, in the BU Ruler intervention, greater perceived frustration correlates with a lower number of collisions.

Table 5.4: Pearson's r coefficient of the number of collisions with respect to the respective subjective ratings. Significant correlations are highlighted.

	Perceived Frustration (Higher: More frustrated)	Perceived Performance (Higher: More flawed)	Perceived Difficulty (Higher: More difficult)
Baseline	-0.04	0.82	0.69
BU Midline	0.66	0.68	0.88
BU Ruler	-0.34	-0.13	0.13
TD Sign	0.03	0.22	0.34

Percent differences (as decimal values) between collisions and subjective differences before and after performance are summarized in Table 5.5. Lower magnitudes indicate a greater congruence of the perceived frustration with the assumed frustration. Positive values indicate a lower assumed value compared to the perceived value.

Table 5.5: Decimal percent differences between the assumed and perceived frustration by intervention.

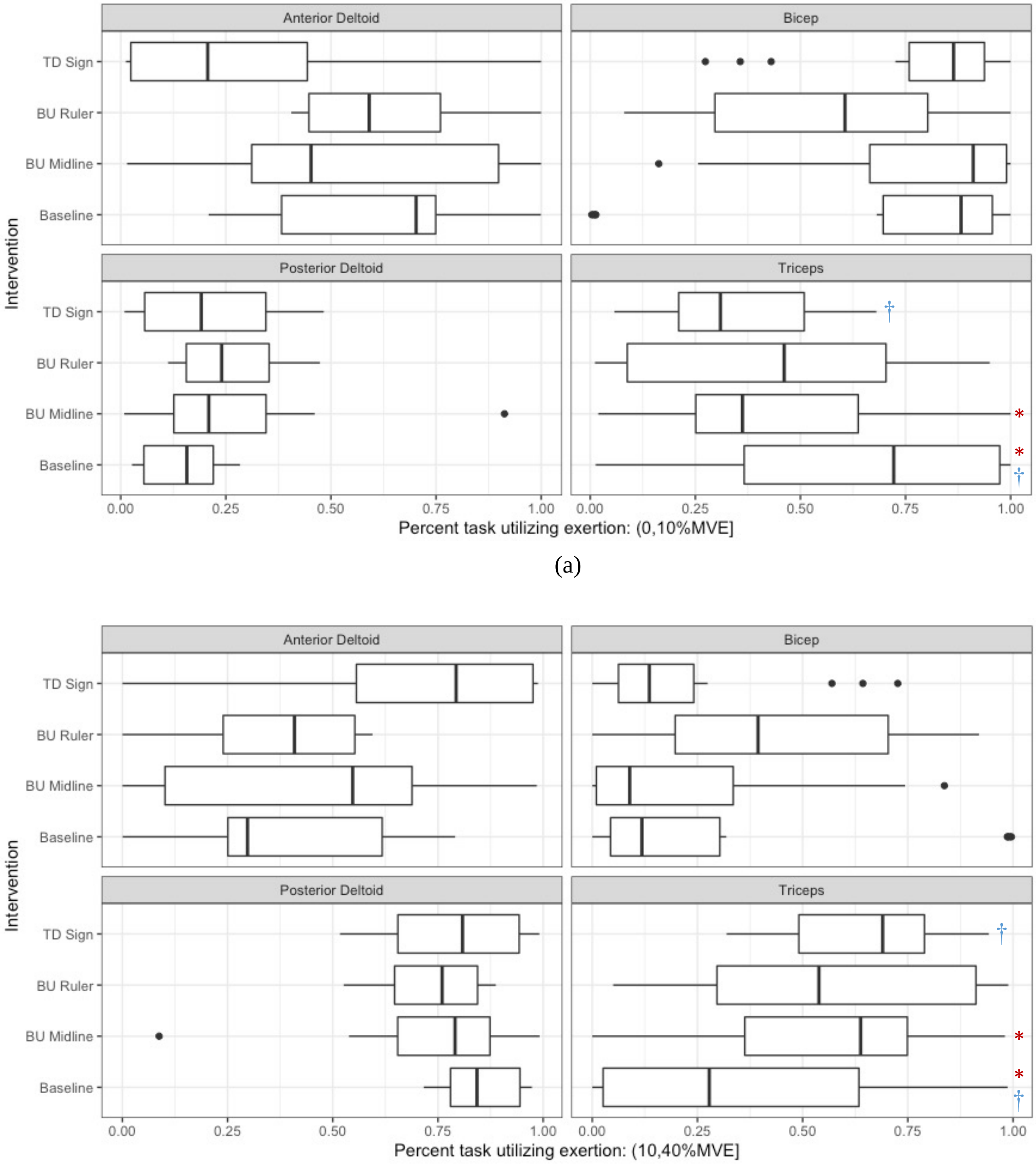
	Baseline	BU Midline	BU Ruler	TD Sign
Assumed vs Perceived Frustration	-0.80 (0.36)	0.39 (0.13)	0.24 (0.35)	0.29 (0.10)

Note: Standard error is noted in parentheses.

5.5.3 Muscular exertion

Muscular exertions normalized to %MVE are shown as a function of the portion of the task in which that level occurred. Only low (0,10% MVE] and moderate (10,40 %MVE] exertions were observed, as illustrated in Figure 5.7.

The triceps exertion duration was significantly longer during the Baseline condition compared to the BU Midline condition ($p < 0.01$). The triceps exertion was also significantly longer and of higher magnitude range during the baseline than the TD sign condition ($p < 0.002$). Statistical significances of interactions and main effects between muscles were not determined, as of no significance in the present work.



(a)

(b)

Figure 5.7: sEMG muscular exertion by intervention type. Statistical significances are indicated with corresponding superscripts. (a) Exertion range (0,10%MVE], (b) Exertion range (10,40%MVE].

5.6 Discussion

5.6.1 Critical events

5.6.1.1 Collision counts

Collisions were the only type of critical event observed in both the Baseline and Intervention conditions. Fewer collisions were observed in the BU Ruler condition than in the Baseline condition. The BU Ruler marks were intended to provide augmented feedback supporting somatorepresentation of the occupied dynamic footprint. The results corroborate this assumption, which indicates that our visuospatial enhancements of the environment can be effective sources of stimuli. Yet interestingly, participants tended to find the BU Ruler intervention as limitedly useful (e.g., 'I didn't understand what they were for.'). This is quite an interesting mixed methods finding as it illustrates that performance benefits may not be consciously perceived. However, such results emphasize a subconscious integration of somatorepresentation, somatosensory information, interpretations of the navigation space, and motor program adjustments. Further, the fact that a functionally useful intervention was subjectively considered 'not so useful' supports the hypothesis that subjective ratings may be an inaccurate depiction of performance-related challenges, particularly among populations where proactive interventions are scarce or nonexistent[73,74,111].

Conversely, the BU Midline was perceived as helpful (e.g., 'It helped me center myself'). However, in terms of influence on collision count, the BU Midline was less effective than the BU Ruler. Although the BU Midline provided clear visual guidance, it is presumed that following the yarn unintentionally constituted a visuo-manual tracking task that required a high level of visual control (i.e., eyes looking down to achieve precision) and thus limited the visual capture of the environment (i.e., the path perspective, walls). In other words, visual tracking conflicted with observing the path to avoid collisions. Hence, the BU Midline condition appears to offer limited effectiveness in terms of visuospatial information regarding the dynamic occupied footprint of the participant and wheelchair. In comparison, the BU Ruler condition did not seem to present a conflicting visual tracking task as ruler lines were (1) noncontinuous along the path and (2) further away from the wheelchair footprint. This behavior is analogous to that of a novice (vehicular) driver who focuses on stimuli on the road immediately in front of the car as opposed to a more experienced driver who observes a broader field of view and is able to gaze further ahead of the car[140]. In sum, the BU Midline provided a salient feedback stimulus that allowed for the conscious adjustment of wheelchair's movements to match a "correct" path *but* did not provide useful information for interpreting the occupied footprint during a dynamic task. On the other hand, by providing consistently spaced lines, the BU Ruler favored the somatosensory processes for extracting and integrating a broader spatial information.

The TD Sign intervention did not appear to reduce the number of collisions committed. This is in line with motor control theory as the signage did not support the motor execution (i.e., no real-time feedback is provided for movement adjustments). Future iterations of this study may examine the number of collisions committed within the first meter of the path as this initial portion is most likely where TD interventions have significant influence. To elaborate, a TD process controls the initial movement made in a feedforward manner rather than using sensory feedback for movement adjustments, so it is hypothesized that the TD Sign intervention would reduce the number of collisions associated with the initial movement during the first portion of the task.

5.6.1.2 Correlation of collisions with perception

Collision counts and perceived ratings were correlated only within the Baseline and BU Midline conditions. Specifically, Baseline trials with high collision counts correlated with performances perceived to be more flawed and of high difficulty. Yet, a higher number of collisions did not correlate to a greater frustration in the Baseline condition. These results suggest that in the absence of augmented visuospatial feedback in the Baseline condition, participants were able to rate their perceived performance with an appropriate level of effective performance and difficulty, but not frustration. Instead, frustration levels in the Baseline condition seemed largely influenced by personal traits (e.g., 'I try to stay positive') or the opinion that a completed task is acceptable regardless of quality (e.g., 'I scrape my walls and hands, but I need to move [to the other room]'). The latter observation highlights the likelihood that people from historically excluded populations might underrate their challenges; such ratings may result in misled design or policy decisions in the absence of performance validation.

The BU Midline condition yielded significant correlations between high collisions and perceived high frustration, more flawed performance, and perceived high difficulty. As discussed previously, it is presumed that the augmented visuospatial feedback from the midline allowed participants, when tracking, to perceive movements more accurately- including their finer, corrective adjustments. Also important to stress, the higher frustration (in the BU Midline condition compared to the Baseline condition) is seen as a positive effect of the intervention as task perception is more congruent with the number of collisions committed. This removes the mismatch between the subjective and effective measures and reduces the influence of personal traits from rating results.

Despite reducing the number of collisions, the BU Ruler did not induce significant correlations between collision counts and subjective ratings. This is in line with motor control theory in that, unlike in the BU Midline condition that consisted of a single salient line in the middle of the path, the BU Ruler consisted of multiple lines which were undoubtedly more difficult to keep track of during motion. As a result, participant's fine, corrective movements were less perceptible in the BU Ruler intervention compared to the BU Midline intervention. Alternatively, it may be presumed that the participants focused mostly on the path directly at their feet during the BU Midline condition (similar to the novice driver previously referenced) then sporadically gaze further ahead. Thus, as a result, the BU Midline condition created two inharmonious tracking tasks: one requiring a broader field of view to track the position of the walls in relation to potential collision courses; and one to look down to track the midline. Hence, frustration would seem elevated in the presence of two rather than one task. While both interventions support BU processes, our results suggest that the BU Ruler intervention more effectively supports the subconscious integration of navigational space information while the BU Midline intervention more effectively supports conscious perception of errors and movements.

5.6.2 Subjective ratings

Within the same 6m straight path-following task, participants reported comparable assumed frustration in all conditions before task execution. This suggests that participants felt that they were completing the same task in all conditions, which is an accurate reflection of the constrained path parameters. Importantly, this reveals that there were no initial biases regarding on the influence of the different intervention conditions. Yet after completing the task, all perceived ratings of frustration, performance quality, and difficulty were significantly different between conditions (with the exception of the TD Sign – Performance).

A reduction of difference between the assumed and perceived frustration was found in all three intervention conditions compared to the Baseline condition. Particularly, a low difference ratio and low standard error was observed for the difference between assumed and perceived frustration during the TD Sign intervention. This result, compared to the lower mean difference ratio but higher standard error for the BU Ruler intervention, suggests that the TD Sign condition was able to "align" task expectation and execution more congruently than the Baseline condition. While the TD Sign did not provide support during the motor action phases, the subjective ratings indicate that it is still beneficial to provide augmented TS visuospatial information for navigation tasks.

Further, only the Baseline condition was associated with higher assumed frustration compared to perceived frustration. This has strong implications for improving confidence in navigation. A higher assumed frustration indicates the task *seems* more difficult than it actually is, potentially due to less-developed, task-dependent motor programs or low self-efficacy in adapting a motor program to a novel navigational space (as in Chapter 3). The findings suggest that augmented (TD) visuospatial information or the promise of augmented (BU) visual feedback over the course of the task reduces the assumed frustration and may hence support confidence in adapting motor programs to novel tasks. On the other hand, the underestimation of assumed frustration may also pose a safety concern if MWUs are unprepared for the task. In this case, the TD Sign intervention was able to support reasonable estimation of movement task.

5.6.3 Muscular exertion

sEMG data were compared across conditions. Significantly longer moderate triceps exertion during the BU Midline and TD Sign conditions than in the Baseline condition were found. Initially, it was hypothesized that lower muscular exertion would be observed across all three intervention conditions; however, the unexpected results are in agreement with previously discussed findings about collisions and ratings.

In the BU Midline condition, it is presumed that the participants treated staying aligned with the midline marker as an additional task (i.e., instead of ‘move through this path’, the task was likely treated as ‘move through this path *along the yellow midline’* or ‘*while tracking the yellow midline*’). Hence, the elevated triceps exertion is likely associated with the sustained propulsion posture for more frequent error correction in movement.

In the TD Sign condition, no BU feedback was provided. Participants likely felt more wary of the path walls after being informed how wide (or how *narrow*, in perspective) the space was. This suggest that the to-scale items used to illustrate the tolerance (i.e., a golf ball; a credit card) were perceived as quite volumetrically smaller than the somatorepresentation of the body. Hence, caution was elevated. However, when muscular exertion results are examined alongside the subjective ratings, we see that, despite the increased postural tension, the initial estimation of space and subsequent movement was more congruent with the post-task perception of performance; this is illustrated by the reduced percent difference between assumed and perceived frustration in the TD Sign compared to Baseline condition. Thus, overall, the TD Sign intervention shows promise in improving MWU’s discernment of navigation space and may support self-efficacy (via increasing the congruence between expectation and reality) and safety.

5.7 Conclusion

This study utilized a path-following task consisting of 6m straight path to compare critical event counts, subjective ratings of the task, and sEMG exertions in conditions providing Enhanced visuospatial information. Two BU intervention conditions (Midline marker, Transverse rulers) and one TD intervention condition (signage detailing the space available) were compared to a baseline (i.e., no intervention) condition. The TD interventions successfully provided augmented visual information to the environment that supported a more accurate internal representation of the navigation space. Conversely, BU intervention conditions successfully provided augmented visual information that supported (1) movement perception within the constrained path and (2) internal integration of spatial information and dynamic occupied footprint. Although the BU Midline intervention was consciously perceived as more useful than the BU Ruler intervention, the ruler marks show promise in providing somatosensory and motor control processes with the spatial information needed to reduce the number of collusions during task execution. The BU Midline intervention unexpectedly created a secondary tracking task that pulled participants' attention down to the ground and inadvertently limited global perception of the navigation space, which may have increased the number of error corrections required.

sEMG results suggest that some degree of postural tension was elevated due to the increased awareness of space, however it is possible that this may also be due to unfamiliarity with interventions that highlight available space and more awareness of tolerances during ADLs may reduce this tension. The space we provided for the task is not narrower than constrained space tasks described by the participants (e.g., tables placed closely at restaurants, boxes stored in hallways). We argue that the provision of information and an accurate sense of how much space is available supports both MWU safety and general awareness of how much space society allots towards inclusion.

In conclusion, findings support the use of simple TD and BU interventions to increase mobility inclusion.

5.7.1 Broader impact and recommendations

This study introduced motor control concepts, specifically seeking to understand the relationship between perception and action. The results may be applied to intervention recommendations for inclusive design. Both TD and BU enhancements can improve mobility and perceived maneuvering towards congruence in MWUs' expectations and reality. This benefit is anticipated to have a positive impact on self-efficacy and overall frustration, both of which may be associated with new environments and recent incidence of a disability[21,111]. From our findings, we recommend the application of simple environmental interventions that augment visuospatial feedback.

5.7.2 Limitations

Although physical disability likely varied within the sample of MWUs, the selection criteria were sufficient to prevent these disabilities from directly interfering with MW maneuvers. However, indirect effects may have contributed to some extent in results variability. Yet such variability is seen as positive, as the impact observed on maneuvering and perception can be more inclusive compared to a sample with a single medical condition and standardized training. Standardized training may also be unrealistic to what people with disabilities actually experience, since training can be inequitable and not reliably offered to MW users[40,41,138]. While the triceps exertion was not considered unsafe in this case, the increase in exertion due to subconscious sensorimotor processes ought to be considered as a part of design endeavors to minimize the development of fatigue. Fatigue, if present over the long-term, may result in poor compensation by other muscle groups, overuse, or musculoskeletal injury.

The length of the path-following task was limited to 6m of straight path. This distance was selected as the exploratory survey (Chapter 3) administered prior to this study indicated that some older MWUs anticipated a need to rest after completing a 5m path task. It is expected that a longer path may reveal greater variations in motor control as a function of path length and fatigue; or increased influence of the secondary tracking task introduced by the BU Midline condition. However, even at minimal levels of fatigue, our results highlight the potential benefits of simple interventions.

Chapter 6 Exploration of Incidence Period on Manual Wheelchair Navigation by Augmented Visuospatial Feedback on Aging Users

6.1 Abstract

Integration of somatosensory information may differ between older adults who age into manual wheelchair (MW) usage and older adults who age with it due to differences in lived experiences and in training during or before periods of age-induced alteration of sensorimotor capability, respectively. Similar differences are likely to distinguish individuals simulating impairment from actual manual wheelchair users (MWUs). This exploratory study compares the effects of augmented visual interventions on path-following performance for aging MWUs with distinctive incidence periods of MW usage (i.e., earlier-in-life, EL vs later-in-life, LL) and age-matched older adults with no incidence (i.e., simulated impairment, SI). Wall path collisions, upper limb sEMG, and subjective perceptions were compared between a Baseline condition with no augmented visual information and three intervention conditions utilizing top-down (TD) and bottom-up (BU) augmented visual information. The TD intervention consisted of a sign depicting lateral tolerance within the path; the BU interventions consisted of (1) a midline traced on the floor along the length of the path and (2) a set of 4 transverse rulers with 2cm lines along their length placed an equidistant interval along the path. The results suggests that the LL group benefited more particularly from the interventions, as wall collisions were fewer and they reported less perceived frustration and task difficulty in the presence of both TD and BU

augmented visual information than in the Baseline condition. However, EMG-based postural tension was higher for the EL group in the TD Sign than Baseline condition, suggesting the EL and LL groups respond differently to intervention types due to a distinct integration of sensory information. The SI group displayed behavior that evidence their significant differences in their somatorepresentation of the situation/context, when compared to MWUs. Overall, enhanced visual information is likely to favor the mobility of MWUs and the incidence period must be considered when investigating the applicability of interventions or the design of guidelines promoting the enhancement of visuospatial information.

6.2 Introduction

In addition to the motivating literature for MW usage and the motor control perspective presented in Chapter 5, the following distinction is made for the present exploration into incidence period and SI.

6.2.1 Incidence of manual wheelchair usage

While a portion of older adults will age with their mobility limitation, recent health trends indicate a rise in mobility disability among the generation approaching old age[32,141]. According to the International Classification of Functioning, Disability, and Health (ICF), an individual's disability is not defined by the medical condition they experience but a mismatch between their capability and the task-environment demand and context[45]. Older adults with later-in-life (LL) incidence of limitations will therefore have different experiences, levels of community support, and functional capabilities compared to older adults who had earlier-life (EL) incidence of limitations[21]. However, research at the intersection of aging and disability often rely on the recruitment of participants based on medical condition (e.g., spinal cord injury) or demonstrated independence. These tendencies may result in samples or implications that do not represent all user needs[46].

From a motor control perspective, those who age into MW usage are likely to have experienced altered mobility capabilities coinciding with age-related declines in gross motor training capability and retention/memory, somatosensory decline, and reduced sensorimotor capability[28,42,43,90,120]. These changes influence one's ICF profile and affect confidence (including psychosocial factors are present when asking for assistance in public; or committing 'errors' in public) and participation, which may further limit opportunities to develop motor skills and improve independence[21,25,49,142,143].

6.2.2 Simulated impairment

Simulated impairment (SI) is defined as the interactive role-playing experience applied to simulate capability loss or limitations[15]. It has been used within early- and late-stage design evaluations of tasks including usability and rely on outcome measurers such as usability/workload scales, spatial and/or physiological metrics[48–52]. In addition to a previously mentioned lack of validation for SI, participants who simulate disability likely have significantly different stresses, emotions related to movement, and lived experiences compared to actual MWUs- all of which contribute to a differing somatorepresentation[21,83,111,135,142,144]. Somatorepresentation supports the generation of movement, therefore it is anticipated that differences in this key cognitive process, transforming sensory information into a body representation, would result in differing movement performance outcomes[83].

6.3 Study aims

The aim of this study was to determine the influence of environmental interventions on a path-following performance for aging MWUs as a function of their incidence period of MW usage and aged-matched simulators of impairment. The participants included three groups: earlier-in-life incidence (EL), later-in-life incidence (LL) and no incidence (i.e., SI). One top-down (TD) and two bottom-up (BU) interventions were designed. The following hypotheses were explored:

> **H1**) The number of wall collisions within a path-following task will be lower in environmental interventions conditions than in the baseline condition. The benefit of an intervention will be greater for LL and SI groups than the EL group.
>
> **H2**) The subjective ratings of assumed frustration and perceived frustration will be more congruent after the intervention than the baseline condition. The benefit will be greater for the LL and SI groups than the EL group.
>
> **H3**) Dominant upper limb muscle activity (sEMG) will be lower in the environmental intervention conditions than in the baseline condition, as uncertainty will be reduced during motion. This effect will be greater for the LL groups compared to the EL and SI groups.

6.4 Methods

6.4.1 Participants

Participants were recruited through online and paper postings at the Disability Network of Washtenaw, Monroe, and Livingston (DNWML, formerly the Ann Arbor Center for Independent Living), senior communities in the greater Ann Arbor area, University of Michigan

(U-M) Health locations such as the geriatric center, Center for Disability Health and Wellness, Turner senior resource center, and the U-M Health Research website. All participants were screened via either email or phone and scheduled for one 2hour experiment session (both Baseline and Intervention studies were 2hours duration).

Participants were recruited with the following inclusion criteria:

- Age 50 years or older
- Wheelchair users: Used a manual wheelchair for at least some mobility support
- Non-wheelchair users: Did not use a manual wheelchair
- Able to independently propel a manual wheelchair for short distances indoors
- No upper extremity prostheses, limitations, or recent injury
- No significant, uncorrected visual, cognitive, or spatial neglect impairment

A total of 38 participants were recruited for the Baseline condition trials, and 33 were recruited for the intervention conditions trials. Seven SI, one EL, and one LL participants performed the two types of trials. Table 6.1 summarizes the participant characteristics from both the baseline and intervention studies.

Incidence period groups were defined with a cut-off incidence age of 45years. This age was selected to avoid overlap between incidence age and years of MW experience predictors since classifying individuals by years of experience may be misleading. For example, two individuals who have used a MW for 10 years may not have comparable experience when viewed from a wholistic ICF profile (e.g., social community, employment opportunities)[21]. Furthermore, gross motor skills learning trends downwards after the age of 40 years[66]. In addition, while short-term improvement of practiced gross motor skill performance following training appears intact and task-specific in old age, the longer-lasting effects of training on performance during aging have not been investigated[42]. Hence, grouping based on years of experience may also be misleading from a motor performance perspective, thus a dichotomous age cut-off was better suited overall.

Table 6.1: Summary of participants.

BASELINE TRIALS						
	EL n = 6		**LL** n = 9		**SI** n = 23	
Age (years)	63.6 (7.3)		61.7 (6.7)		60.2 (9.2)	
Sex	Female: 3 (50%) Male: 3 (50%)		Female: 7 (77.8%) Male: 2 (22.2%)		Female: 15 65.2%) Male: 8 (34.8%)	
Dominant handed grip strength (kg)	22.7 (9.9)		21.2 (7.1)		24.0 (8.0)	
Dynamic occupied width (cm)	75.6 (9.0)		77.1 (5.0)		78.7 (1.6)	
Neck range of motion (degrees)	Left 57.7 (26.5)	Right 51.8 (19.4)	Left 67.4 (7.6)	Right 62.2 (7.6)	Left 71.0 (8.6)	Right 69.1 (8.3)
INTERVENTION TRIALS						
	EL n = 7		**LL** n = 6		**SI** n = 20	
Age (years)	60.6 (7.0)		61.2 (7.0)		58.8 (7.0)	
Sex	Female: 5 (71.4%) Male: 2 (28.6%)		Female: 4 (66.7%) Male: 2 (33.3%)		Female: 16 (80%) Male: 4 (20%)	
Dominant handed grip strength (kg)	17.0 (8.2)		20.9 (6.9)		23.1 (6.6)	
Dynamic occupied width (cm)	74.9 (6.4)		74.5 (4.6)		75.4 (1.7)	
Neck range of motion (degrees)	Left 50.7 (22.1)* p = 0.005	Right 49.1 (26.1)** † p = 0.00001	Left 64.2 (11.5)	Right 62.2 (7.6) †	Left 68.0 (16.7)*	Right 71.3 (10.0)**

EL: Earlier-in-Life incidence; LL: Later-in-life incidence; SI: Simulated impairment. Standard deviation or percentiles are shown in parentheses, as respectively appropriate. Overall, lower occupied widths were observed in the Baseline condition (i.e., main effect); no interaction effects between other demographic factors and occupied width were found.

Age and current biological sex (as opposed to current gender) were self-reported. Grip strength was an average of three dominant-handed trials using a hand dynamometer. Dynamic occupied widths were measured using an anthropometry caliper with the participant seated in the wheelchair, assuming a propelling posture with the widest width as determined through visual observation. Widths were measured knuckle-to-knuckle as this was the widest distance within the height of the cardboard panels. A goniometer measured the neck range of motion while the participant remained seated in the wheelchair. Statistical significance was only found within neck range of motion among the Intervention study participants, with EL participants having lower ranges of motion compared to the LL and SI groups.

6.4.2 Materials

Materials are as detailed in Chapter 5 with the following distinction. The Baseline condition as well as the TD Sign, BU Midline, and BU Ruler interventions are unaltered from Chapter 5.

6.4.2.1 Manual wheelchair

A MW was provided for 3 of 6 EL and 5 of 9 LL baseline; and 3 of 7 EL and 4 of 6 LL intervention participants requested its use (e.g., did not own a device and relied on devices provided by public spaces; preferred to use our device rather than traveling with their own). No transfers were permitted due to health and safety precautions. All SI participants utilized the lab MW.

6.4.3 Procedure

The study was approved by the U-M Institutional Review Board. Informed consent was received for all participants. The corresponding procedures are detailed in Chapter 5.

6.4.4 Analysis

As an exploratory examination, statistical significance will be reported however the inflated Type I error due to the sample size and number of comparisons made resulted in low effects sizes for all analyses. p-values less than 0.05 are reported for all examinations as opposed to defining a corrected alpha.

Descriptive graphs representing collision counts and subjective performance ratings by group are used to compare baseline with interventions. A 3x4 ANOVA was performed and p-values are noted. As in Chapter 5, only the 8cm lateral tolerance is examined. Pearson's correlations were used to examine the relationship between collision counts and subjective ratings (i.e., Frustration, Performance, Difficulty). The difference between assumed and perceived frustration is examined via percentage difference. The "*stats*" package in R studio was used for the data analysis. Interaction effects are not examined in any ANOVA results (e.g., EL-Baseline results are not compared to LL-TD Sign results). Qualitative comments were considered towards a mixed methods understanding of performance results.

All raw sEMG signals, including the MVE trials, were band passed filtered by a 2nd order Butterworth 10-500Hz, then the RMS signal was computed using 0.25sec windows with 0.0625sec window overlap. Muscular exertion was defined as a percentage of MVE (%MVE). RMS signals were normalized using the respective muscle MVE signal, and histogram distributions for exertion levels were generated. Histograms bins were categorized by muscular exertion: Low (0-10%MVE], Moderate (10-40%], High (40-80%MVE], Extremely High (80-100%MVE].

6.5 Results

6.5.1 Wall collisions

The Baseline condition was characterized by significantly greater collisions committed by the LL group than the EL group (p = 0.04) and the SI group (p = 0.02) (Figure 6.1). However, within each of the three intervention conditions the differences between group collision counts were not significant. In other words, unlike in the baseline condition, the LL group did not commit more collisions in the intervention conditions.

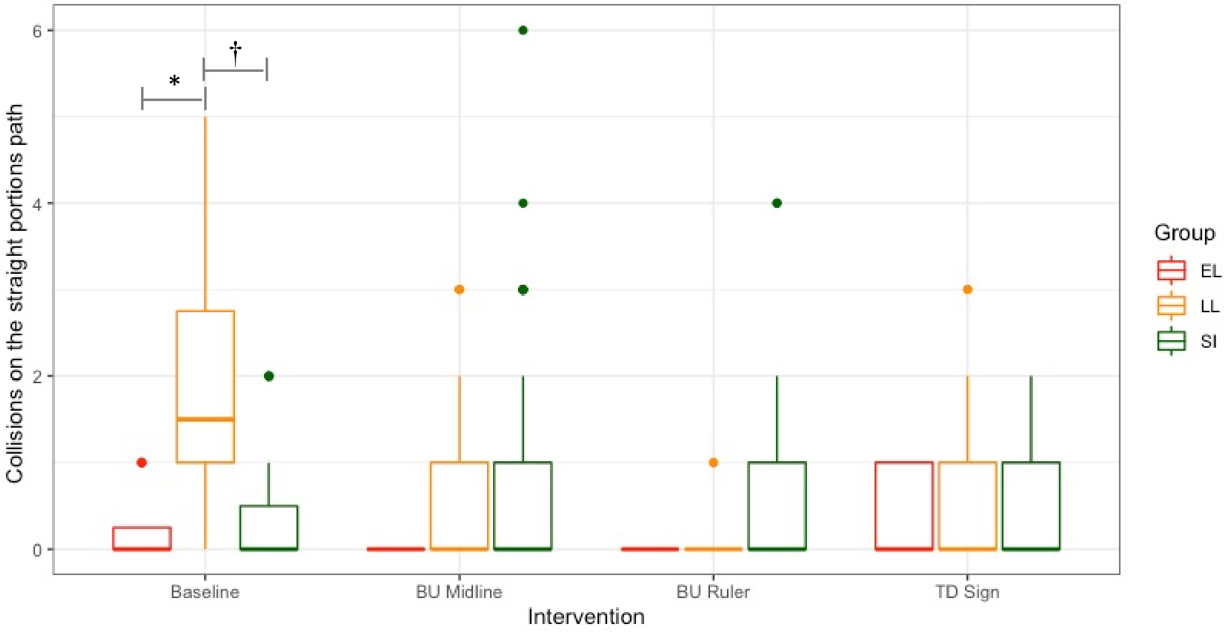


Figure 6.1: Collisions committed along the straight portions of path. *Note: BU: Bottom-up intervention; TD: Top-down intervention; EL: Earlier-in-life; LL: Later-in-life; SI: Simulated impairment*

6.5.2 Subjective ratings

Frustration ratings (Figure 6.2) were collected both before Trial 1 and after Trial 3 of each condition. Performance and difficulty were only assessed after Trial 3. All groups reported comparable assumed frustration across all conditions. However, the LL group reported significantly higher perceived frustration in the Baseline condition than the EL group ($p < 0.0002$) with significant reduction across all intervention conditions ($p < 0.002$). No group difference in perceived frustration was found in the intervention conditions. Similarly, the LL group reported significantly higher perceived performance and difficulty compared to other groups in the Baseline condition ($p < 0.0006$) with significant reduction across all interventions ($p < 0.001$). The perceived performance or difficulty in any intervention condition was not significantly different between groups. Furthermore, the SI group also reported significantly reduced difficulty in the BU Midline and TD Sign conditions than in the Baseline condition ($p < 0.004$).

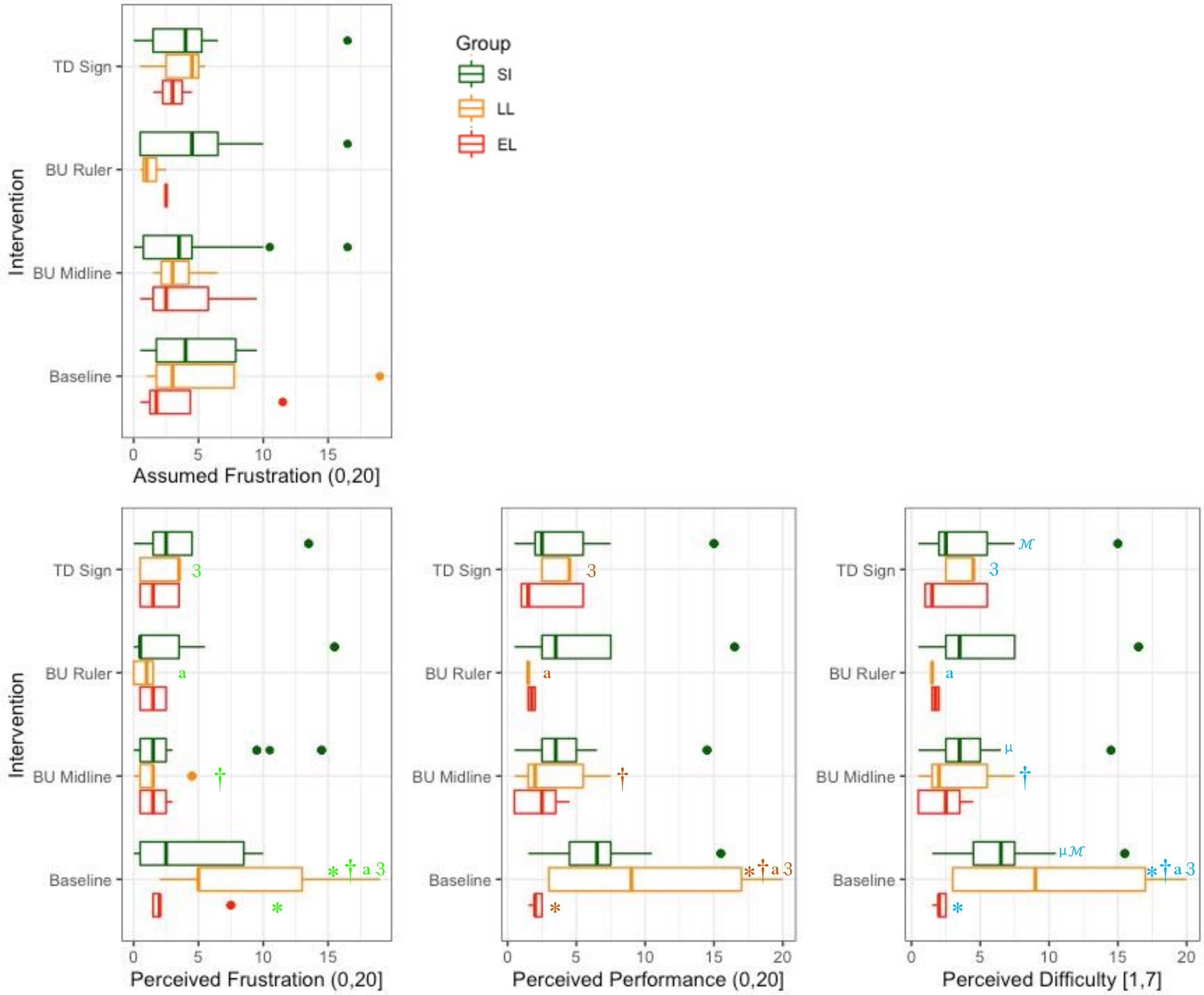


Figure 6.2: Summary of the respective subjective ratings. Standard deviation in parentheses. Statistical significance between the intervention types is indicated with corresponding superscripts. *Note: All $p < 0.004$.*

Correlations between collisions committed and subjective ratings by group and study condition are summarized in Table 6.2. Positive r values indicate that high subjective ratings (defined in the table) are correlated to a high number of collisions. For example, for the EL group in the Baseline condition, a perception of high frustration is correlated to a high number of collisions. On the other hand, negative r values indicate a high rating correlates with a low number of collisions. For example, for the LL group in the Baseline condition, greater perceived frustration correlated with a lower number of collisions.

Table 6.2: Pearson’s r coefficient of the number of collisions with respect to the respective subjective ratings. Significant correlations are highlighted.

EL			
	Perceived Frustration (Higher: More frustrated)	Perceived Performance (Higher: More flawed)	Perceived Difficulty (Higher: More difficult)
Baseline	0.99	0.45	0.71
BU Midline	N/A (0 Collisions)	N/A (0 Collisions)	N/A (0 Collisions)
BU Ruler	N/A (0 Collisions)	N/A (0 Collisions)	N/A (0 Collisions)
TD Sign	0.07	0.15	0.00
LL			
	Perceived Frustration (Higher: More frustrated)	Perceived Performance (Higher: More flawed)	Perceived Difficulty (Higher: More difficult)
Baseline	-0.82	0.82	0.81
BU Midline	0.85	0.79	0.90
BU Ruler	-0.47	N/A (0 Collisions)	0.25
TD Sign	0.00	0.45	0.37
SI			
	Perceived Frustration (Higher: More frustrated)	Perceived Performance (Higher: More flawed)	Perceived Difficulty (Higher: More difficult)
Baseline	-0.08	0.28	0.21
BU Midline	0.01	0.06	0.07
BU Ruler	0.46	0.52	0.47
TD Sign	-0.11	0.24	-0.06

Note: Significant correlations were highlighted if they were greater than 0.60.

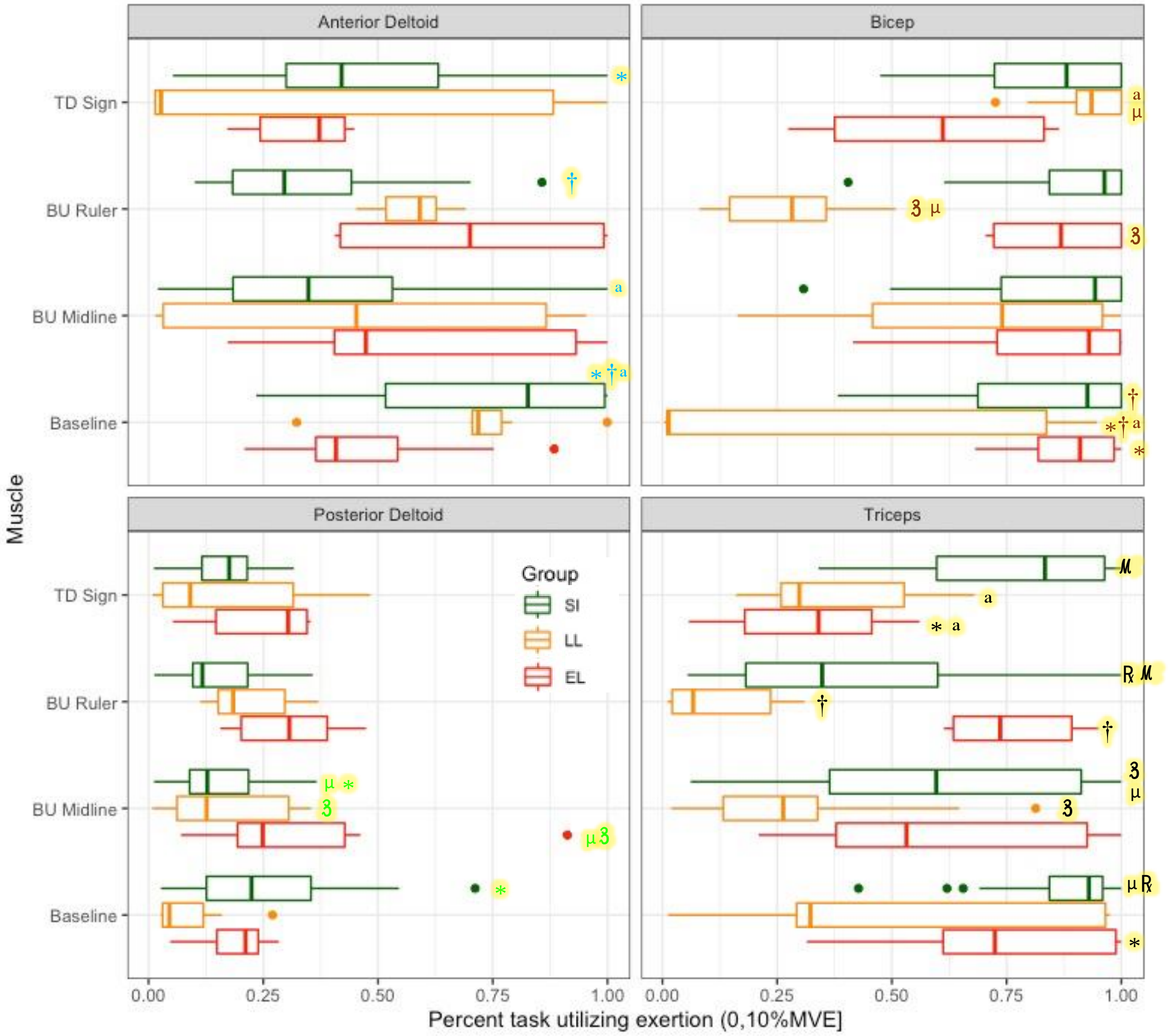
Study conditions where no collisions occurred had no respective correlation coefficient by definition. Conversely, a correlation coefficient of 0 was found for all conditions where ratings and collisions were equally and oppositely spread out. As such, no interpretation is available for the EL group-BU intervention conditions.

High correlation values were found most consistently for the LL group Baseline and BU Midline conditions. No significant correlations were observed for the SI group.

6.5.3 Muscular exertion

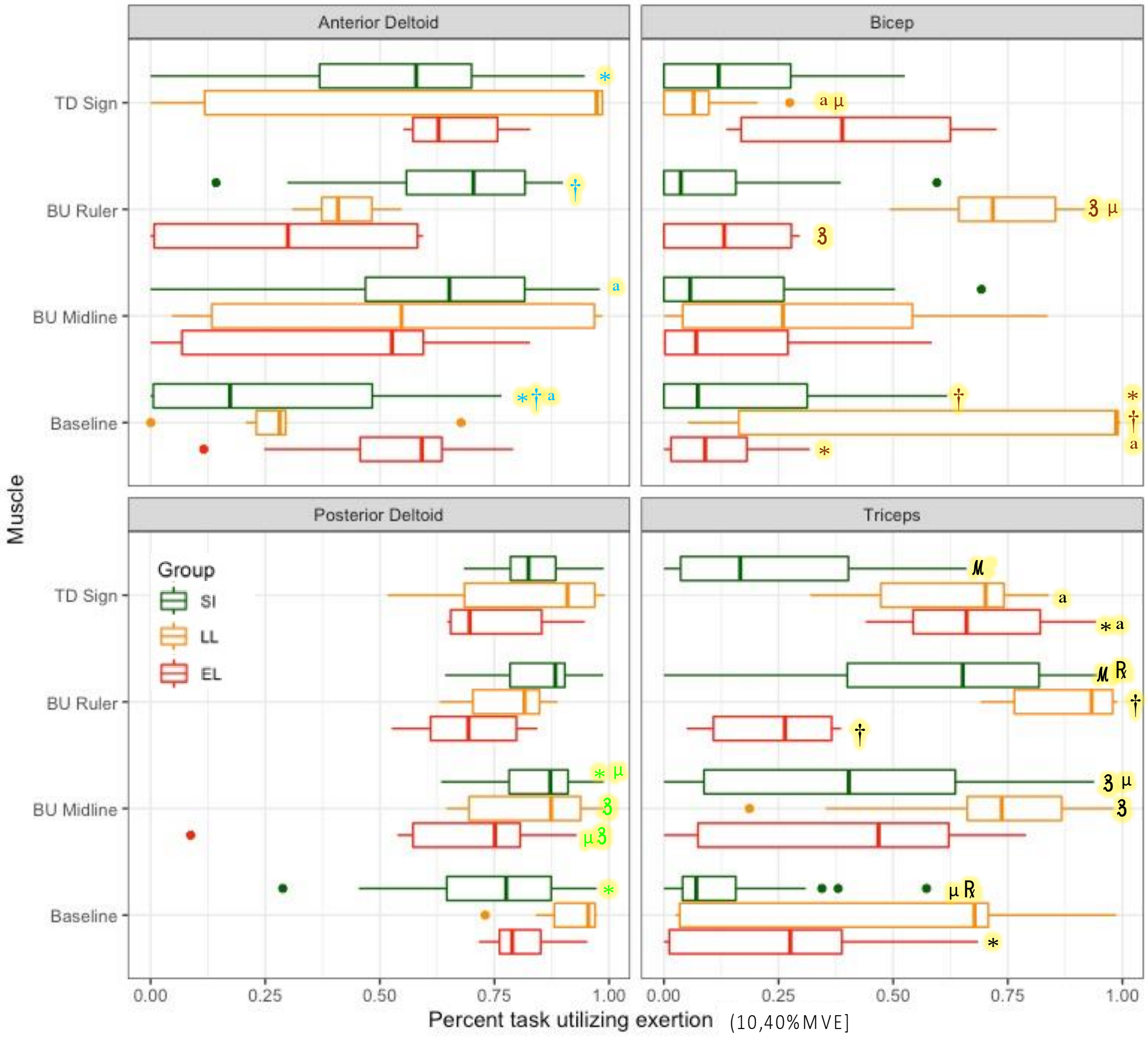
Muscular exertion durations in %MVE are presented in Figure 6.3 as a function of the normalized portion of task in which that muscular exertion was used. Only low (0,10%MVE] and moderate (10,40%MVE] exertions were observed. Note that low and moderate exertions are complimentary per each muscle.

Statistical significance of normalized muscular exertion was observed for all muscles across varying groups and study conditions. Of note, longer anterior deltoid exertion was recorded in the SI group-TD Sign condition compared to the Baseline condition; increased triceps exertion was recorded in the EL group in the TD Sign condition compared to the Baseline condition. This EL increase notably led to longer triceps exertion by the EL group compared to the LL group in the TD Sign condition.



(top)

Figure 6.3(top): sEMG muscular exertion by intervention type. Statistical significances are indicated with corresponding superscripts. (top) Exertion range (0,10%MVE], (bottom; next page) Exertion range (10,40%MVE]. Note: All * are $p < 0.03$; all other p values are $p < 0.004$.



(bottom)

Figure 6.3(bottom): sEMG muscular exertion by intervention type. Statistical significances are indicated with corresponding superscripts. (top; previous page) Exertion range (0,10%MVE], (bottom) Exertion range (10,40%MVE]. *Note: All * are p < 0.03; all other p values are p < 0.004.*

6.6 Discussion

6.6.1 Critical events

6.6.1.1 Wall collisions

Baseline differences were characterized by significantly greater collisions committed by the LL group than the EL and SI groups. These differences suggest that the usual (i.e., commonly employed) context of MW navigation leaves those with LL incidence of MW usage at a mobility disadvantage compared to age-matched peers who experienced incidence earlier in life. However, it is unlikely that years of MW experience or earlier-in-life training was the source of EL vs LL differences since the SI group, who have never used a MW and thus do not have any experience beyond this lab experiment, *also* committed significantly fewer collisions than the LL group.

While it is difficult to determine the source of group differences from this exploratory study, one interpretation may be related to the somatosensory processes involved in motor control. Specifically, for the LL group may not be as familiar with postures and subsequent representations of body in space than for the EL group, even while utilizing the same visual stimuli from the path. Somatorepresentation would also be less precise in the LL than the EL group, thus contributing to the greater number of collisions in the Baseline condition. On the other hand, the SI group's somatoperception of bodily location within their surroundings and capability perception may be more precise compared to the LL group because both (posture and stimuli) have remained comparatively consistent with their lifelong experiences-- for the LL group, somatoperception and capabilities have recently changed with the onset of disability. Hence, the SI group was able to control their motor actions with fewer errors compared to the LL group.

No group differences were observed in any of the three intervention conditions (Figure 6.1). This indicates that both TD and BU interventions can improve LL performance so as to match the level of the EL and SI groups. The augmented visual information compensated for any somatosensory process alterations unique to the LL. If the EL group were significantly hindered by their reduced neck range of motion (see Table 6.1), a greater number of collisions would have been expected as they would have less visual feedback from their surroundings and/or the floor, per the corresponding intervention conditions. As this was not the case, we believe that motor programs developed via the long-term experience of the EL group allowed them to adapt and perform well in all task conditions.

Results also suggest that the EL group did not benefit as much from the interventions compared to the LL group. This is congruent with the hypothesis that individuals affected later-in-life would more strongly benefit from interventions since their motor programs were unable to adapt comparably on their own.

6.6.1.2 Correlation of collisions with perception

Significant correlations between the number of collisions and perceived aspects of performance were only observed for the EL and LL groups. Correlations were not significant for SI group. Comments from SI participants during and after movement trials are in agreement with this finding. Multiple SI participants mentioned that the study was “fun” and reflected on how they would feel if the simulation were “real”; one participant stated that she would have been more frustrated if the simulation was “actually real”. Overall, this finding supports the hypothesis that SI is not able to accurately represent the perceptions of people with disabilities.

Among the EL participants, higher collision counts were associated with greater perceived frustration and higher perceived difficulty in the Baseline condition. However, a high number of collisions did not correlate with poor perceived performance. This was reflected in comments collected in the present and previous studies (e.g., ‘I finished, therefore it was fine’; ‘I was able to do it’)[73,74]. Ergo, relying on subjective ratings alone may thus bias evaluations. However, in the Baseline study, a mismatch between collision counts and perceived performance was not observed for the LL group. This group difference can likely be accounted for by a difference in somatorepresentation. Specifically, the LL group may be more conscious of how committing errors or struggling appears to others compared to the EL group who may have become more comfortable with their disability and how it is perceived by strangers[25,83].

High positive correlations were also observed for the LL group in the BU Midline condition. This is expected to result from the high salience of the midline marker. As discussed in Chapter 5, following the midline was likely treated as a tracking task that might have been sporadically interrupted by gazing to the environment (to check on the spatial perspective of the MW between the walls). Movements that deviated from the midline were more clearly perceived while tracking. This intervention shows promise in aligning perceived and effective action by providing an accurate magnitude of trajectory deviation, which can support the development of MW maneuvering motor programs for those with LL incidence of disability.

6.6.2 Subjective ratings

Within the same 6m straight path-following task, participants reported comparable assumed frustration in the Baseline and all three intervention conditions. This suggests that participants perceived all conditions as the same task; in other words, regardless of visual enhancements present, all trials were still considered similar, which reflects the reality of path tolerance and distance. Yet, within the Baseline study, the LL group rated their perceived frustration as significantly higher compared to the EL group despite similar assumed frustration ratings. This suggests that the LL group may experience a greater mismatch between their perceived capabilities (which are used to plan their motor actions and thus their initial expectation of the task) and their actual capabilities (which influences the actions executed).

For the LL group, perceived frustration and difficulty were rated lower in all intervention conditions than the Baseline condition. This trend was not observed for the EL group. This difference suggests that interventions provided some support to the perception of the task for the LL group. Further, a reduction in perceived frustration and difficulty may also have a positive influence on confidence and self-image in somatorepresentation.

6.6.3 Muscular exertion

In the Baseline condition, the moderate bicep exertion was significantly longer for the LL group than the EL and SI groups. This bicep exertion is likely associated with fine adjustments of MW motion or posture control. Such effect may be influenced by the differing somatorepresentations between groups; specifically, the apprehension regarding psychosocial factors/experiences and their more recent capability alterations is likely greater for the LL than the EL group[21,25]. The SI group are not likely experiencing such emotions due to the temporary nature of simulation since multiple comments expressed feelings of “fun” “temporary” nature of the task[15,48,52].

Interestingly, for the LL group the moderate biceps exertion duration was shorter in the TD Sign than in the Baseline condition. The TD nature of the intervention (i.e., not providing feedback of movements) likely caused participants to be more wary of the path walls after knowing how wide (or how *narrow*, in perspective) the space was. Some comments like “Oh, no way I can do this!” were expressed, suggesting some anticipation *and* acceptance of collision occurrences. Yet for the EL group, moderate triceps exertions were significantly longer in the

TD Sign condition than the Baseline condition. Following the same logic, it is possible that the EL group found familiarity in the task and was able to recall motor programs of similarly constrained situations whereas the LL group had not yet acquired the corresponding repertoire. A future mixed methods examination of this finding could reveal new insights on how to support older adults who age into disability and their self-efficacy, self-image, and perception of psychosocial stressors. Regardless, elevated triceps exertion suggests that the to-scale items used to illustrate the tolerance (i.e., a golf ball and a credit card) were perceived as quite small compared to the somatorepresentation of the body in the MW. Hence, caution was elevated, as reflected in the longer exertions of the triceps which contribute to fine movement adjustments and weaker propulsions.

For the SI group, anterior deltoid exertion durations were higher in all intervention conditions than the Baseline condition. High anterior deltoid exertion is associated with large propulsion movements. From these results, we believe the interventions boosted SI confidence which allowed them to make broader movements through the path. Interestingly, longer moderate bicep exertions were also observed in the BU Midline and BU Ruler interventions. This is in agreement with the above interpretation that the SI group made broader movements which led to requiring more corrective actions in these conditions. Higher bicep exertions were, however, not observed in the TD Sign intervention, suggesting that the TD visuospatial information boosted confidence but the lack of BU visuospatial feedback on path deviation led to the SI group not perceiving errors in their trajectory.

6.7 Conclusion

This study utilized a path-following task consisting of 6m straight path to compare critical event counts, subjective ratings of the task, and sEMG exertions across two BU interventions (midline marker, transverse rulers) and one TD intervention (signage detailing the space available) compared to a baseline (i.e., no intervention) condition. The results suggests that the LL group more particularly benefited from the interventions. Perceived frustration and difficulty of task was reduced in the presence of both TD and BU interventions for LL and SI groups. Collision counts were also reduced, resulting in comparable performance between all three groups as opposed to significantly higher number of collisions by the LL group in the Baseline condition. sEMG signals revealed lower durations of exertions associated with tense posture control when visual feedback of an "ideal" path was provided, which expresses a relaxation and a likely reduction of muscle fatigue over time. It may be speculated that reductions in muscle exertions could also contribute to a reduction of upper limb and shoulder MSDs that impact MWUs[145]. However, SI showed limited validity when comparing subjective ratings and muscular exertion patterns observed for the EL and LL group.

In conclusion, findings support the use of simple TD and BU interventions towards increasing mobility inclusion in constrained movement tasks, particularly for those who age into mobility limitations.

6.7.1 Broader impact and recommendations

A perspective on motor control was included in this study. Hence, the proposed interventions are intended to target specific pain points within motor control, particularly for those who are most disadvantaged in performance, namely the LL group in the present case (further supported by Chapter 3 results). Intervention recommendations and inclusive design will benefit from a perspective that takes into account factors affecting sensorimotor abilities. Our findings also suggest that the recruitment of people who aged into MW usage may benefit differently from interventions compared to those who have aged with their disability. However, the present results should not be interpreted as implying that the EL population does not benefit from interventions. A greater sample size is needed to increase the power from these exploratory findings. From our findings, we recommend the application of simple interventions that augment visuospatial feedback to MWUs.

Further, we recommend the direct recruitment of older MWUs when outcome measures relate to or rely upon maneuverability or muscular exertion as SI may bias results.

6.7.2 Limitations

The study sample was too low to assess the statistical significance of analyses to the desired power. Hence, all p-values were reported in this exploratory analysis. A larger sample size would increase the power of analyses performed. Many challenges and barriers to recruitment occurred during the span of the Baseline and Intervention studies. Notably, the COVID-19 pandemic and its lingering effects greatly reduced willingness to participate in the studies. Populations with mobility disabilities are more likely to be more negatively impacted by COVID-19, and avoidance of COVID-19 exposure is logical and understandable. It is important to highlight that such lingering effects also included a significant reduction in staffing for transportation and assistive services that many people with disabilities require to have inclusive access to mobility. Scheduling for services such as A-Ride was/is significantly strained, as communicated by multiple participants. Further, parking at U-M North Campus was greatly reduced due to new parking regulations, construction (that also blocked the already-limited public accessible parking), lack of assistance from parking services to adapt a solution despite multiple requests and viable propositions. Many MWUs who participated in the Baseline study communicated frustration and unwillingness to participate in future studies taking place on North

Campus. We highly recommend accessible parking to all buildings on North Campus be properly allocated to effectively improve U-M's DEI culture.

Participants across all groups noted the similarity between the task and a vehicular driving; in future iterations of this study, a questionnaire regarding driving experience and skill may be included.

Although physical disability may have ranged within the sample of MWUs, the applied selection criteria were sufficient to prevent these disabilities from directly interfering with manual wheelchair maneuvers. However, indirect effects (e.g., emotions of past experiences, disability-related stress) may have contributed to some extent in results variability[51,135]. Yet such variability may be seen as a benefit, since the influence on maneuvering and perception can be more inclusive than in using a population sample affected by a single medical condition and submitted to a standardized training. Standardized training may also be unrealistic relative to what people with disabilities actually experience, since training can be inequitable and not reliably offered to MWUs[40,41,138]. Further, as health conditions were not controlled, no restrictions were applied to the SI group (i.e., no range of motion restrictions were applied). Validity of simulation suit to replicate physical performances of the 'replaced through simulation' population have only recently began to be evaluated in the literature[16].

The length of the path-following task consisted of 6m of straight path. This distance was selected as the exploratory survey administered prior to this study (Chapter 3) indicated that some older MWUs anticipated needing to rest at as low as 5m path length, It is expected that a longer path may highlight group differences related to maneuver control along pathways of lengths more comparable to building hallways and public spaces. However, even at minimal levels of fatigue, our results highlight the potential benefits of simple interventions.

Chapter 7 General Discussion and Future Work

This dissertation investigated ways in which human factors and motor control theories can improve task-environments and the design/evaluation process for manual wheelchair users (MWUs), in order to be more inclusive. MWUs with later-in-life (LL) incidence of use were of particular concern. Human sensorimotor functions and internal motor planning were a focus to consider their influence on performance and mobility, as illustrated in Figure 7.1

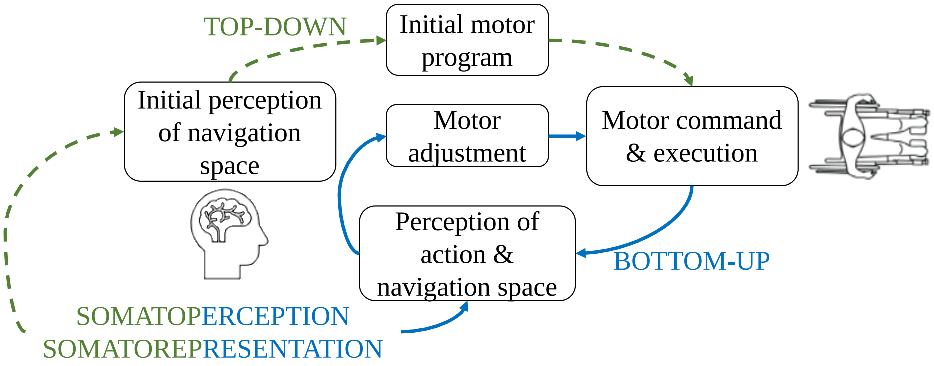


Figure 7.1: Motor planning and action loop; highlighting concepts.

7.1 Summary of major findings

7.1.1 Invalidation of simulated impairment

The validity of simulated impairment (SI) in the assessment of MWU mobility performance was tested in Chapter 4. The minimum clearance required to perform a collision-free parallel parking (PP) task was used as an outcome measure. The results showed:

- SI participants were not representative of MWUs since task representation and somatorepresentations of the body do not equate between the two groups.
- Although mean values presented some similarity, the *range* of minimum PP clearances required was lower for the SI than the MWU group. This has significant implications on design ranges/the definition of user needs (e.g., 5th to 95th percentile performance measures).
- As the dynamic occupied depth was smaller for the MWU than the SI group, it was assumed the larger PP space necessitated by the MWU group was most likely due to differences in sensorimotor processes/abilities rather than an effect related to the MW.
- Altered somatoperception and somatorepresentation Of MWUs likely contributes to differing internal body representations and thus differing motor planning between the MWU and SI groups.
- The greater magnitude and more prolonged moderate biceps muscle activity for the MWU than the SI group, is likely due to greater precision of movements and postural tension in the former. This suggests that the use of SI in research would not allow the estimation of the true range of sEMG outcomes for MWUs.

Validity of SI to represent mobility disability has not been assessed in literature. Our findings (Chapter 4) suggest that the reliance on SI participants in lieu of MWUs reduces the range of mobility performance outcomes and thus impacts any standard deviation or 5th – 95th percentile considerations[48,52,75]. In addition, sEMG results revealed that more movements/ corrections (particularly finer movements characterized by greater postural tension, i.e., higher EMG activity) were performed by the MWU than the SI group while tested in the same task. It is hypothesized that due to differing somatorepresentations and vulnerabilities to negative psychosocial emotions that cannot be replicated in a temporary disability simulation, motor control goals (e.g., a stronger focus on how others may perceive mistakes by the MWU group) and execution styles are not comparable between groups[15,19,83]. This hypothesis is supported by comments from MWU reflecting on real-life experiences during/after tasks while SI participants reflected on the "fun" and temporary aspect of simulations.

The inclusion of SI within this investigation supports interpretations based on somatoperception and somatorepresentation rather than years of experience as a main contributing factor. This view can improve how MWUs are recruited within studies and provide an empirical example of the value in recruiting MWUs rather than SI participants in design and research endeavors.

These results can be applied to universal and inclusive design practice as they highlight invalidity and biases in using SI in the present context. Hence, the direct recruitment of aging wheelchair users is recommended when outcome measures relate to or rely upon maneuverability or muscular exertion. Encouragingly, the recommendation to "recruit disability voices in research and practice" was also echoed at the 2023 Center for Disability Health and Wellness (CDHW) Symposium by its hosts[146]. This alignment of our results within human factors engineering to the current consensus and advocacy within disability studies is encouraging and strongly backs our conclusions.

7.1.2 Motor control-informed interventions

In Chapter 5, the influence of enhanced visuospatial information on MW mobility performance was investigated in a path-following task using four different conditions: baseline control (no intervention), a posted sign indicating the lateral tolerance (i.e., MW-wall gap), a midline on the floor, and a transverse ruler at regular intervals. Performance was assessed by the number of collisions and a comparison to Baseline results:

- In the TD Sign condition, the number collisions did not appear to be reduced. However, the congruence between performance expectation and execution were better aligned than in the Baseline condition (i.e., assumed and perceived frustration were aligned).
- The MWU participants perceived the BU Midline as helpful (e.g., 'It helped me center myself'). This is because the BU Midline provided salient feedback that favored *conscious* movement adjustments towards matching a "correct" path. Yet the BU Midline did not provide sensory information as effectively as the BU Ruler condition towards *somatosensory interpretations* of the dynamic footprint. On the other hand, the BU Ruler condition was perceived as 'not as helpful', but it provided a greater degree of sensory information that promoted the integration of the MW's dynamic occupied space. While the BU Midline only provided information about a "correct" path, the BU Ruler's transverse markings provided information about the available tolerance, thus allowing for more precise positioning between the walls. It may be presumed, then, that following the midline alone (and *not* gazing up at the walls as well) was perceived as insufficient in avoiding collision, even though an accurate following of the midline would have, by definition, resulted in zero collisions- otherwise, participants would have looked only at

the midline and not the walls. This could be interpreted as a lack of confidence in the intervention, resulting in the incidence of a secondary tracking task, as summed below.

- It is speculated that the BU Midline condition inadvertently produced a secondary tracking task that encouraged participants to focus their gaze directly in front of the MW (approximately the footrests/feet) in order to precisely line their movement to the "correct" midline path. The midline tracking task likely felt "easier" than the avoidance of collisions, but it divided visual attention between the floor and the path. The BU Ruler condition, on the other hand, promoted a gaze that naturally included the path ahead within the field of view and was thus more effective in promoting the integration of the occupied dynamic space.
- Moderate triceps exertion (10, 40%MVE] were longer in the BU Midline and TD Sign conditions than in the Baseline condition. Presumably, this is respectively due to the induced precise following task (i.e., careful following of the midline) and the wariness of width (or rather, the narrowness) of path, both of which leading greater postural tension and more fine exertions to adjust movement trajectory.

The application of simple, augmented visuospatial feedback into the environment appears to facilitate MW navigation and mobility. The TD intervention appears to successfully provide a more accurate internal representation of the navigation space, which effectively promotes a more accurate perception of errors compared to MW movements without intervention. Conversely, BU interventions provided augmented visual information that supported (1) perception of movements and their resulting errors within the constrained path and (2) internal integration of spatial information and dynamic occupied footprint.

At the 2023 CDHW Symposium, both the hosts and keynote speaker notably highlighted the importance of finding inclusive interventions that “are naturally there”, that is to support human functions with available tools[146]. The interventions explored in this dissertation show great potential in this regard. Firstly, intervention implementation is relatively simple compared to interventions that require structural changes (e.g., widening hallways). The BU Midline and BU Ruler interventions in particular can be highly adjustable/adaptable to improve navigation both in static and shifting environments; for example, hallways frequently encumbered with obstacles (see **Error! Reference source not found.**), workspaces with moving furniture, or restaurants with movable tables.

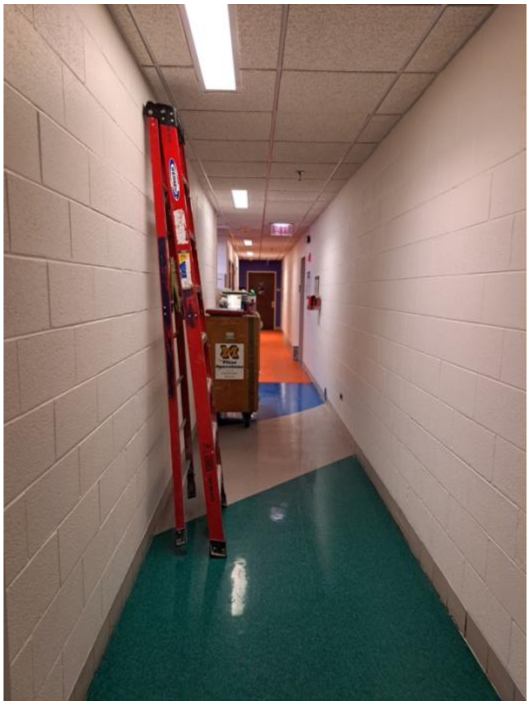


Figure 7.2: Obstructed hallway creating a narrow, constrained path due to movable storage. This image was taken on a different day from the image in Chapter 1 in the U-M Industrial and Operations Engineering (IOE) building where data collection took place during the numerous months of construction (Ironically, construction was towards improving inclusion with U-M campus’s first multi-stall gender neutral restroom.). While items were ‘easily’ moved (depending on the individual) and ‘temporary’ (other locations may not be so willing as IOE’s building manager, who immediately address this), barriers without any accessibility support reduces inclusion and imposts negative psychosocial factors.

7.1.3 Incidence period of manual wheelchair usage

A preliminary survey study (Chapter 3) investigated whether the incidence period of manual wheelchair (MW) usage (i.e., earlier- or later-in-life incidence; EL and LL, respectively) influences motor actions as characterized by subjectively estimated path-following performance across a variety of environmental factors. This survey revealed:

- Significant differences between the EL and LL groups in the context of mobility performance and motor planning.
- Estimated performance was rated lower by the LL group than the EL group, and comments revealed the conscious integration of knowledge (i.e., regarding functional capabilities and experiences). It was hypothesized that the LL group's underlying motor programs were less trained, which led to an exhibition of lower confidence and thus lower estimated performance when compared to the EL group.
- Skewed somatorepresentation within the LL group (anticipated to be due in part to "emotional attitudes" and being unaccustomed with psychosocial factors related to their new situation) likely contributed to lower performance estimation than the EL group.

The results from this initial investigation guided the subsequent intervention study and exploratory analyses (Chapters 5 and 6).

Chapter 6 explored the influence of incidence period and simulated impairment (SI) using data from the Baseline and Intervention trials.

- In the Baseline condition, the LL group committed a greater number of collisions than both the EL and SI groups. The comparable number of collisions for the EL and SI groups suggests that years of experience may not be as strong a contributor as originally suspected, since the SI group's MW experience is limited to this study. This supports conjectures of EL and LL differences as well as MWU and SI differences in sensorimotor processes.

- Among the EL participants, higher collision counts were associated with greater perceived frustration and higher perceived difficulty in the Baseline condition. Yet, a high number of collisions did not correlate with poor perceived performance. EL comments reflected the internally-formed goal of simply completing the task, despite instructions to aim for collision-free performance (e.g., ‘I finished, therefore it was fine’)[73,74]. On the other hand, the LL group demonstrated higher correlations between greater collisions and poor performance. This group difference was likely due to a difference in somatorepresentation where the LL group was more conscious of how committing errors resulting from their altered capability appears to others while the EL group may have become less affected by this over time, as indicated by the internally-formed goal[25,83].
- Moderate bicep exertion in the Baseline condition was significantly longer for the LL group than the EL and SI groups. As above, this was likely influenced by the LL group’s somatorepresentation being more cognizant of psychosocial factors and their more recent capability alterations compared to the EL group.
- For the SI group, anterior deltoid exertion durations were higher in all intervention conditions compared to the Baseline condition. This result suggests a greater degree of confidence characterized by broader strokes (propulsion powered by the shoulders rather than the bicep/triceps) for the SI group than the EL and LL groups. An “in practice” use of SI in this case would have contributed to an overestimation of subjective influence on interventions. Further, no significant correlations were found between the number of

collisions and perceived performance for the SI group; this supports the hypothesis that simulated impairment cannot produce the somatorepresentation of MWUs. Thus, SI appears invalid for the representation of subjective usability, workload ratings, and muscular exertions.

Our results highlight avenues in which dividing the aging MWU population by incidence period can benefit design/human factors by considering the somatosensory processes of people with disabilities. Hence, the uniqueness and strength of this dissertation project is emphasized.

Both somatoperception and somatorepresentation provide a novel frame of reference for examining task-environment pain points and potential areas for targeted interventions. Our recruitment criteria controlled for visual impairments and spatial neglect that may otherwise have influenced input pathways for somatorepresentation. Hence, it may be assumed that differences in perception and task representation are influenced by the incidence period[88]. It is postulated that recent impairment led to "emotional attitudes" that skewed somatorepresentation (that is, 'knowledge of the body' or 'body alterations') within the LL group[92].

This new perspective contributes not only to the understanding of how aging into disability affects central processes but also the understanding of variables that should be considered by the International Classification of Functioning, Disability, and Health (ICF). Adding incidence period to either the 'Health Condition' or 'Personal Factors' boxes can provide health care practitioners with useful estimates regarding *what* individuals need to learn about their functional capabilities (somatoperception) and *how* they may perform tasks and feel affected by psychosocial factors (somatorepresentation)[21,45,111].

7.2 Limitations and future work

Health condition was not screened under participation criteria. This decision was made to adhere to the ICF view of disability when considering the influence of incidence period of disability; and to capture the intersectionality of disability which was encouragingly highlighted in 2023 CDHW Symposium, as differences between health conditions “compound” across design decisions[48,146]. Although physical disability may have differed between MWUs (e.g., lower limb amputation; spinal cord injury, etc.), the applied selection criteria were sufficient to prevent these disabilities from directly interfering with MW maneuvers (i.e., no upper limb limitations). However, indirect effects (e.g., condition-specific or access-dependent rehabilitation; visibility of condition that may impact psychosocial factors), may have contributed to some extent in results variability. To combat this, neck range of motion and grip strength were collected to ensure matched capabilities between groups[49,147]. It is interesting, however, to note that the variability among MWU participants is rather a positive outcome supporting our claim that SI is not appropriate to infer inclusive design. Future work may consider additional selection criteria based on health condition to increase controlled variables between participants. For example, selection of spinal cord injury (SCI) patients from the U-M Michigan Medicine system may have the added benefit of controlling for training and physical therapy exposure. (Conversely, recruiting MWUs from diverse health care systems would add variability since training and therapy type/retention would largely vary[40,41,138,148].) However, while SCI patients were not strictly recruited for our investigations, our recruitment material was shared in related spaces. One reason we did not see a large population of SCI participants is that our recruitment was heavily hindered by the limited access of the participants to the University of Michigan North Campus (e.g., inaccessible parking, mobility access). Future work must first resolve accessibility barriers, otherwise recruitment by health condition will likely prove difficult.

Combinations of interventions were not examined. Bottom-up intervention results suggest that a combination of BU Midline and BU Ruler may provide an overall intervention that not only supports the somatosensory process but also *feels* useful to MWUs. However, it is possible that a combination of interventions may provide an overabundance of attentional captures or bottom-up stimuli[97]. For example, the BU Midline task unintentionally created a secondary tracking task that drew participants' visual gaze and field of view away from potential points of collision; therefore, the addition of a BU Midline (that induced a tracking task) could in fact reduce the effectiveness of the BU Ruler. Hence, future work is needed to consider interaction effects of multiple interventions.

Other manipulations of the environment may also yield further understanding of the somatoperception and somatorepresentation integration of information. Obstacles with varying shapes and sizes or MW add-ons/modifications that alter the wheelchair's size (e.g., baskets, bag hooks) may benefit from different augmented visual feedback. For instance, adding a side mirror to the MW to view the ground near the rear wheel, but the rear view may conflict with the visual task of avoiding collisions up ahead. The addition of the mirror may also increase task complexity and thus the task completion times as users may feel compelled to attend all visual tasks. Analogously, novice drivers may struggle to divide attention between all views (front, side, and rear of the car), with numerous endogenous shifts in attention prior to developing the appropriate motor programs/capabilities via training[149].

Continuing with the mirror add-on example, prolonged use of tools may impact somatosensory processes. Examinations of mobility performance prior to and after training with the mirror can inform how adjusted somatoperception may impact the utilization and effectiveness of intervention conditions; in other words, training can facilitate the integration of two types of information[83]. For example, familiarity with the mirror may actually improve the effectiveness of the BU Midline task if a greater understanding of the MW's occupied footprint is gained with the mirror. Similar examinations of the plasticity of somatoperception and somatorepresentation processes may also be applied to the SI group to determine whether longer training mitigates the SI biases found in the present study. However, it is anticipated that longer SI training sessions may diminish its 'convenience' (compared to the perceived 'inconvenience' of recruiting of actual MWUs)[15,48,75].

Required 'High' muscular exertions were not examined. While this finding casts suspicion upon the use of SI in examinations of strength and ease of maneuverability in wheelchairs, the present study did not specifically investigate measures of strength or situations of high exertion. The examination of ramp inclines (e.g., **Error! Reference source not found.**) with SI compared to MWUs would address this gap. Both incline angles equal or greater than ADA limits, which are conditions reflected in many real world environments, may be included in future studies to determine whether group differences exist between SI and MWU capabilities[50,130]. From the present study, differences in range of capability would also be important to consider, particularly if an LL group of MWUs experiences greater difficulty compared to SI or EL groups (e.g., Chapter 6). Such investigations could provide guidance for a future iteration of ADA transportation or building ramp requirements, which could have great impact on the accessibility of automated vehicles and independent living[49].

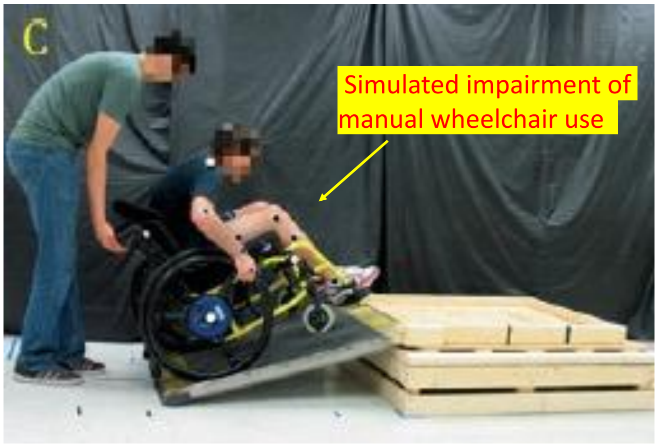


Figure 7.3: Example of a ramp propulsion by an SI participant equipped with sEMG sensors [50]. Adapted from Bertocci et al. (2018) investigating muscular exertion on ramp inclines measured in situ from local transit.

Experience was not directly examined. While our questionnaires (Chapters 3, 5, 6) provided data regarding MW usage and frequency (e.g., Question 2.3 in Appendix C, which was also used the Baseline and Intervention trials), our sample size did not permit covariate analyses. A larger sample size in a future study would improve the statistical power of our results. Furthermore, it was impossible to assess the number of hours in which participants typically used a MW in daily life; many factors (e.g., weather, day-to-day health and pain) impact MW usage, and beyond years of experience, experience may be difficult to examine.

Also, participants in both the SI and MWU groups noted the similarity between mobility tasks and a vehicular operation; in future iterations of this study, a questionnaire regarding driving experience and skill may be included. While driving and MW propulsion differ vastly in their motor actions, the field of view required to track all potential points of collision and the visuo-manual tracking task induced by the BU Midline may be influenced by driving experience. Thus, it is hypothesized that a transfer from such learning could be utilized to design effective ways to present information (e.g., following familiar sign rules of the road with respect to clearance or where signs are placed).

7.3 Final Conclusion

In addressing the hypotheses defined in Chapter 1, this dissertation concludes that:

C1) Interventions to augment visuospatial information within the environment can support mobility performance for aging manual wheelchair users (MWUs), in terms of a reduction of collisions and improved congruency between subjective and objective performance measures (i.e., improved motor action perception and thus resulting performance) (Chapter 5).

C2) Incidence period groups within a larger aging MWU group yielded insights regarding mobility performance and influence of interventions. Specifically, those with later-in-life incidence of MW usage no longer committed significantly more collisions compared to their earlier-in-life peers, however, they also appeared to be more impacted by intended stressors (e.g., awareness of narrowness within the space) (Chapter 6).

C3) The simulation of impairment (i.e., MW usage) yielded differing baseline maneuverability needs (Chapter 4) and mobility performance outcomes (Chapter 6) compared to MWU trials, which invalidates their use for design and research purposes.

Appendices

Appendix A: Summary of Participants

A total of 108 participants aged 50 years and above were recruited for this dissertation. Table Appendix Table A.1 summarize the number of participants in each study.

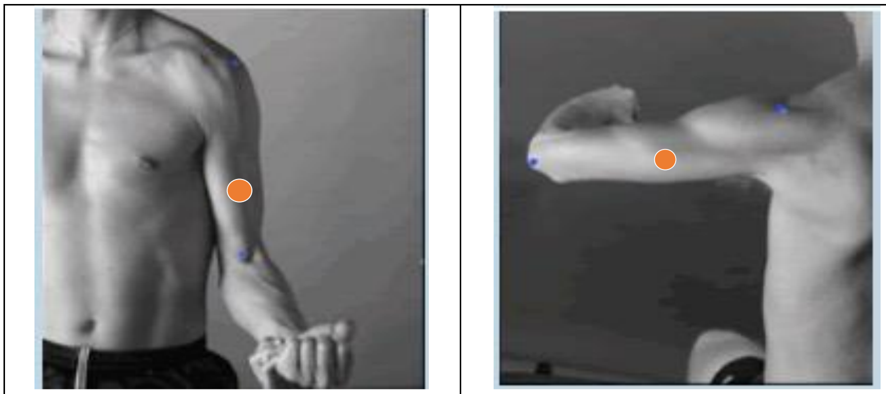
Appendix Table A. 1: Summary of the number of participants in each study.

	EL (Incidence age < 45 years)	LL (Incidence age ≥ 45 years)	SI
Survey (Chapter 3)	10	27	0
Parallel park trials (Chapter 4)	13	15	43
Baseline trials (Chapter 5-6)	6	9	23
Intervention trials (Chapter 5-6)	7	6	20

Overlap was not assessed with the survey study (Chapter 3). All participants in the Baseline and Intervention trials (Chapter 5-6) performed the parallel park maneuver assess in Chapter 4. One EL, one LL, and seven SI participants completed both the Baseline and Intervention trials.

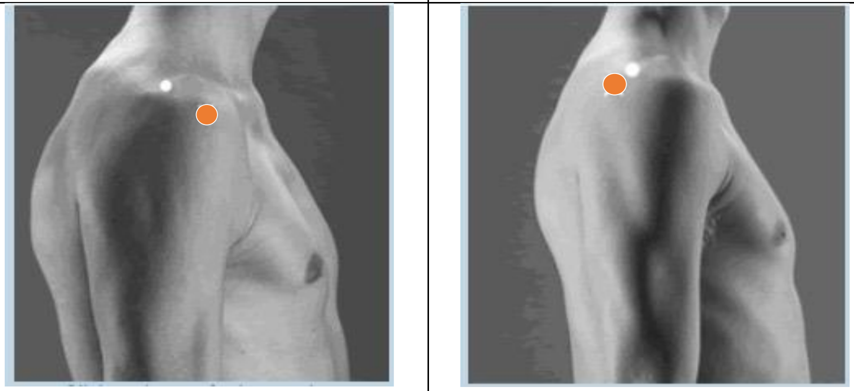
Appendix B: Placement of Electrodes

Electrodes to assess sEMG signals were placed on the dominant arm bicep, triceps, and anterior and posterior deltoid muscles, as in Appendix Figure B.1.



Bicep

Triceps



Anterior deltoid

Posterior deltoid

Appendix Figure B. 1: Electrode placement on the dominant arm at the orange dot locations. Images adapted from the SENIAM Project (from the Biomedical Health and Research Program – European Union) to increase visibility. The white dots in the deltoid images mark boney landmarks used to find placement location.

Appendix C: Copy of Survey (Chapter 3)

The survey (Chapter 3) was administered online via Qualtrics. A copy is reproduced beginning on the following page. Note formatting changes that prevent tables from being shown on the same page in this adapted version (e.g., Question 2.3 is separated from its associated table).

Assumed Manual Wheelchair Performance and Confidence – Adults 50+

(HUM00197832)

Thank you for your interest in our research study.
You are invited to voluntarily participate in this study investigating performance and confidence for **manual wheelchair usage by adults aged 50+**.

If assistance is needed, you may complete this survey with or on behalf of a family member, client, or other associate.
You may skip questions you are not comfortable answering.

Results of the study will be used towards recommendations for improving inclusive spaces (like offices and public buildings).

The survey is **estimated to take 10-15 minutes** and asks about:

- General demographics
- Your experience and current usage of a manual wheelchair
- How you expect to perform in some wheelchair tasks

As part of their review, the University of Michigan Health Sciences and Behavioral Sciences Institutional Review Board (IRB) has determined that this study is no more than minimal risk and exempt from on-going IRB oversight.

Compensation for Participation

On the final page, you may enter your name, contact information (phone or email), and mailing address for a $10 gift card.

SECTION 1 of 3

Please tell us about yourself, to help us understand your situation.

1.1 What is your age? __________Years

1.2 What is your biological sex?

- ○ Male
- ○ Female
- ○ Prefer not to say

1.3 What is your hand dominance?

- ○ I am Right-handed.
- ○ I am Left-handed.
- ○ I am Ambidextrous.
- ○ Not sure or Not applicable

1.4 Please rate your vision (when wearing your glasses or corrective lens).

- ○ Good
- ○ Fair
- ○ Poor

1.5 What is your height?

__________ Feet (ft)
__________ Inches (in)

1.6 What is your weight? ______________ Pounds (lbs.)

1.7 What is your combined weight with your wheelchair?

If you don't know: Don't worry, it is OK to estimate or skip.

______________ Pounds (lbs.)

SECTION 2 of 3

Please help us understand your manual wheelchair usage and experience.

2.1 At what age did you begin using a manual wheelchair? ______________ Years

2.2 What is the primary reason you started using a manual wheelchair? Please select **one**.

○ I have an age-related reason(s).

○ I have a medical condition(s).

○ I have a temporary situation(s).

○ Other reasons. Please specify: ____

2.3 For each of the following activities, how do you typically use a manual wheelchair?

Note: Consider “assistance” as assistance in propelling the wheelchair (e.g., pushing).

	With assistance	Without assistance	I do not use a manual wheelchair for this
Move within a room, indoors	○	○	○
Move between rooms, indoors	○	○	○
Move through a hallway, indoors	○	○	○
Move within indoor workspaces (e.g., office)	○	○	○
Move within indoor public spaces (e.g., grocery store, hospital)	○	○	○
Move outdoors, along a sidewalk	○	○	○
Move outdoors, not on a sidewalk (e.g., grassy park, dirt path)	○	○	○
Move and travel in vehicles (e.g., taking bus or rail trips)	○	○	○

If you do not use a manual wheelchair for any of these tasks,
please specify what activities you do typically use a manual wheelchair for:

2.4 If you use a manual wheelchair indoors: Do the indoor spaces you move around in have smooth or soft flooring?

- ○ Mainly smooth flooring, like hardwood or tiles.
- ○ Mainly soft flooring, like carpet or rugs.
- ○ I move around equally on smooth and soft flooring surfaces.

2.5 For each of the following activities, how often do you <u>typically</u> use a manual wheelchair?
If you typically perform none of these tasks, please skip.

	Multiple times per day	Once per day	At least once per week	Less than once per week
Move within a room, indoors	○	○	○	○
Move between rooms, indoors	○	○	○	○
Move through a hallway, indoors	○	○	○	○
Move within indoor workspaces	○	○	○	○
Move within indoor public spaces	○	○	○	○
Move outdoors, along a sidewalk	○	○	○	○
Move outdoors, not on a sidewalk	○	○	○	○
Move and travel in vehicles	○	○	○	○

2.6 As of now and <u>on your own</u>, how **confident** are you that you can move your manual wheelchair....

	Not confident at all	Slightly confident	Moderately confident	Very confident	Extremely confident
...over carpet?	○	○	○	○	○
...around furniture?	○	○	○	○	○
...over thresholds, such as at front doors?	○	○	○	○	○
...in small spaces, such as a bathroom?	○	○	○	○	○
...up a standard wheelchair ramp?	○	○	○	○	○
...down a standard wheelchair ramp?	○	○	○	○	○
...up a dry ramp that is steeper than usual?	○	○	○	○	○

2.7 As of now and <u>on your own</u>, how confident are you that you can open, go through, then close a standard 32", lightweight door?

- ○ Not confident at all
- ○ Slightly confident
- ○ Moderately confident
- ○ Very confident
- ○ Extremely confident

As of now and <u>on your own</u>, how confident are you that you can open and go through **a spring-loaded door**?

(That is, a door that automatically swings shut, for example at malls.)

- ○ Not confident at all
- ○ Slightly confident
- ○ Moderately confident
- ○ Very confident
- ○ Extremely confident

SECTION 3 of 3

Please help us understand how you use your manual wheelchair.

INSTRUCTIONS:

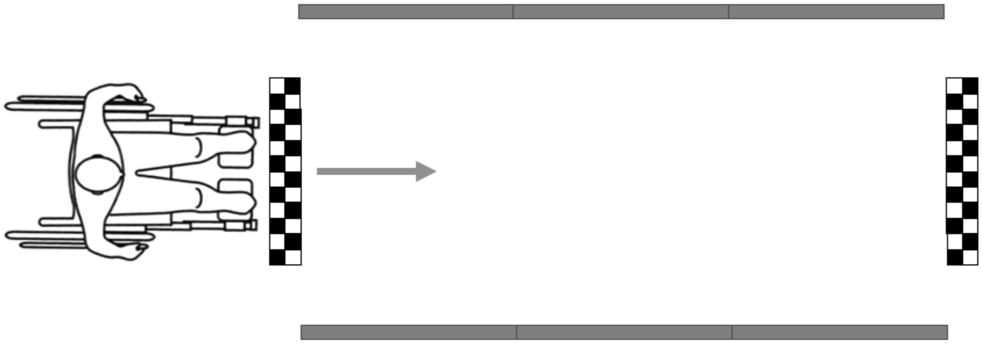
On each of the following pages, we will ask you to consider a manual wheelchair task and answer a few questions. For each task, an explanation is provided, along with an illustration.

Consider each task as being performed on your own, **without** assistance.

Task 1 of 9

Roll forward a short distance and stop.
Walls form a moderately wide path around your wheelchair, with approximately **6in (15cm) on either side.**

Goal:
Move to the end of the hallway, marked by the finish line.
Avoid bumping into the walls.
Move as safely and quickly as possible.



If asked to perform this task today, could you?

○ Yes, I could do this task safely and very well.

○ Yes, I could do this task safely, but not well.

○ No, I could not do it.

How confident are you that you could do this task safely and consistently?

○ I am very confident.

○ I am only somewhat confident.

○ I am not confident.

Task 1 of 9 (Continued)

Do you expect any of the following to occur?
Please select all that apply.

☐ I expect to bump into a wall.

☐ I expect to go slowly or take a long time.

☐ I expect I would need to rest before I reach the finish line.

☐ Other, please specify: ____________________

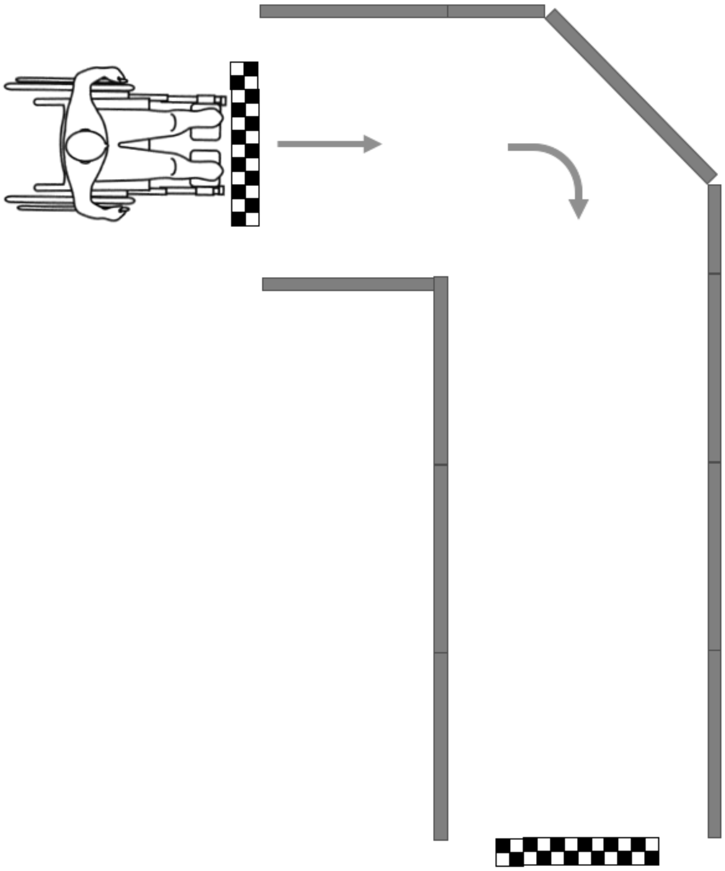
☐ No, I do not expect any of these to occur at all.

Task 2 of 9

Roll forward, make a right-hand turn, roll forward a short distance, and stop. Walls form a moderately wide path around you, with approximately **6in (15cm) on either side**.

Goal:

Move to the end of the hallway, marked by the finish line.
Avoid bumping into the walls.
Move as safely and quickly as possible.



If asked to perform this task today, could you?

○ Yes, I could do this task safely and very well.

○ Yes, I could do the task safely, but not well.

○ No, I could not do it.

Task 2 of 9 (Continued)

How confident are you that you could do this task safely and consistently?

○ I am very confident.

○ I am only somewhat confident.

○ I am not confident.

Do you expect any of the following to occur?
Please select all that apply.

☐ I expect to bump into a wall.

☐ I expect to go slowly or take a long time.

☐ I expect I would need to rest before I reach the finish line.

☐ Other, please specify:

____

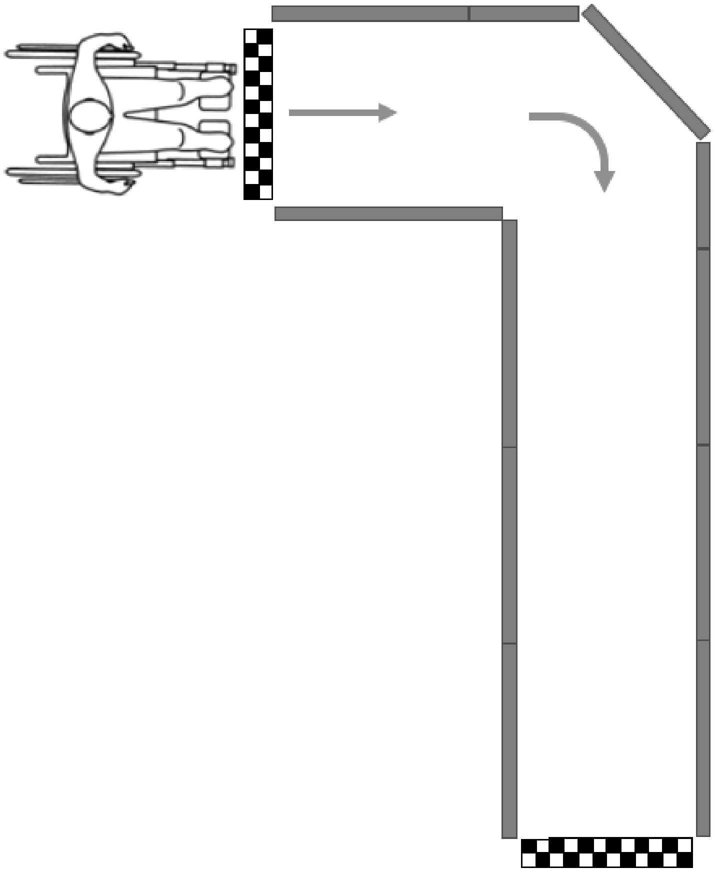
☐ No, I do not expect any of these to occur at all.

Task 3 of 9

Roll forward, make a right-hand turn, roll forward a short distance, and stop. Walls form a <u>narrow</u> path around you, with approximately **2in (5cm) on either side**.

<u>Goal:</u>

Move to the end of the hallway, marked by the finish line.
Avoid bumping into the walls.
Move as safely and quickly as possible.



If asked to perform this task today, could you?

○ Yes, I could do this task safely and very well.

○ Yes, I could do the task safely, but not well.

○ No, I could not do it.

Task 3 of 9 (Continued)

How confident are you that you could do this task safely and consistently today?

○ I am very confident.

○ I am only somewhat confident.

○ I am not confident.

Do you expect any of the following to occur?
<u>Please select all that apply.</u>

☐ I expect to bump into a wall.

☐ I expect to go slowly or take a long time.

☐ I expect I would need to rest before I reach the finish line.

☐ Other, please specify:

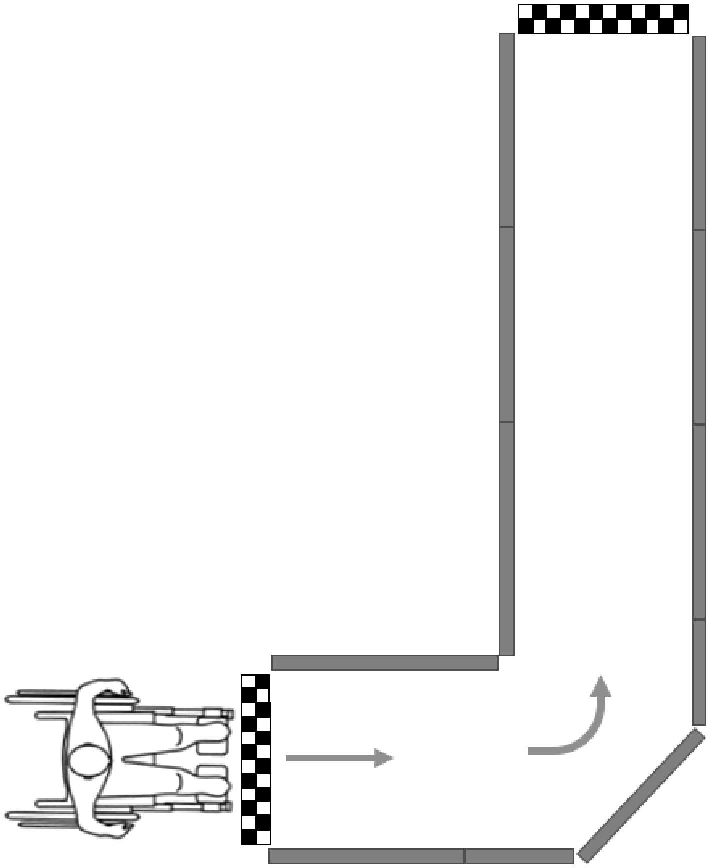
____

☐ No, I do not expect any of these to occur at all.

Task 4 of 9

Roll forward, make a left turn, roll forward a short distance, and stop.
Walls form a narrow path around you, with approximately **2in (5cm) on either side.**

Goal:
Move to the end of the hallway, marked by the finish line.
Avoid bumping into the walls.
Move as safely and quickly as possible.



If asked to perform this task today, could you move in this path to the end of this hallway?

○ Yes, I could do this task safely and very well.

○ Yes, I could do the task safely, but not well.

○ No, I could not do it.

Task 4 of 9 (Continued)

How confident are you that you could do this task safely and consistently today?

○ I am very confident.

○ I am only somewhat confident.

○ I am not confident.

Do you expect any of the following to occur?
Please select all that apply.

☐ I expect to bump into a wall.

☐ I expect to go slowly or take a long time.

☐ I expect I would need to rest before I reach the finish line.

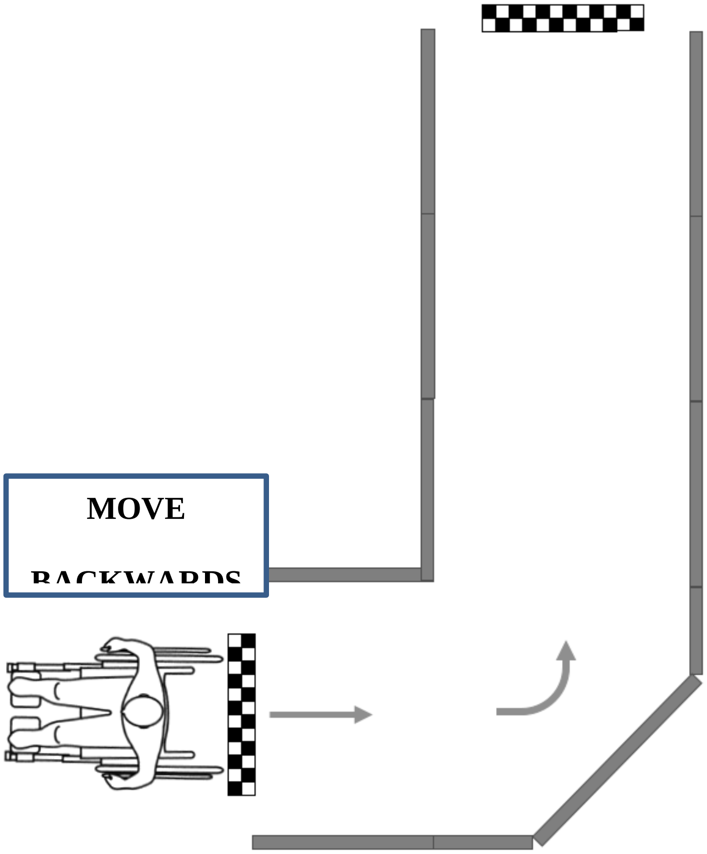
☐ Other, please specify: ____________________

☐ No, I do not expect any of these to occur at all.

Task 5 of 9

Roll backwards, make a backwards-right turn, roll backwards a short distance, and stop.
Walls form a moderately wide path around you, with approximately **6in (15cm) on either side**.

Goal:
Move to the end of the hallway, marked by the finish line.
Avoid bumping into the walls.
Move as safely and quickly as possible.



If asked to perform this task today, could you move in this path to the end of this hallway?

- ○ Yes, I could do this task safely and very well.
- ○ Yes, I could do the task safely, but not well.
- ○ No, I could not do it.

Task 5 of 9 (Continued)

How confident are you that you could do this task safely and consistently today?

○ I am very confident.

○ I am only somewhat confident.

○ I am not confident.

Do you expect any of the following to occur?
Please select all that apply.

☐ I expect to bump into a wall.

☐ I expect to go slowly or take a long time.

☐ I expect I would need to rest before I reach the finish line.

☐ Other, please specify:

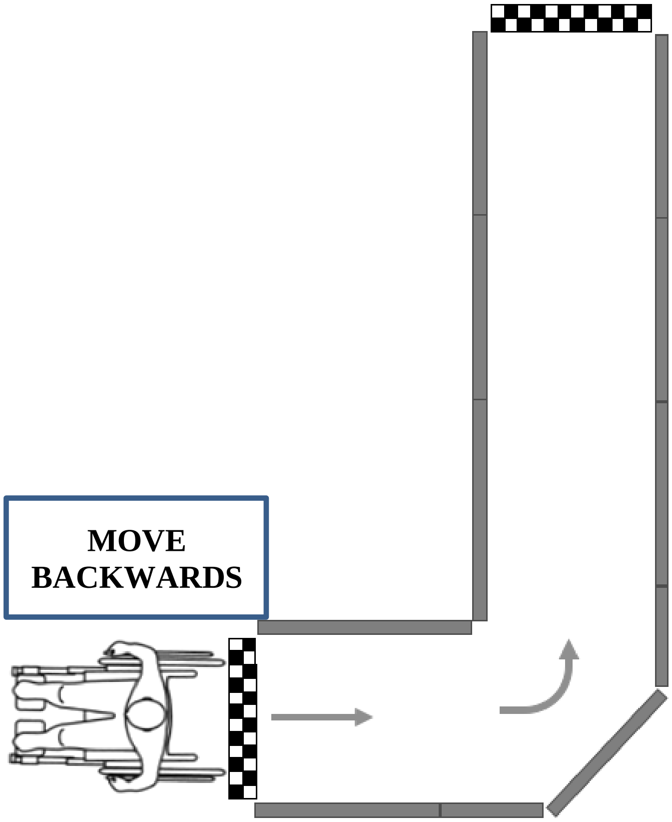
____

☐ No, I do not expect any of these to occur at all.

Task 6 of 9

Roll backwards, make a backwards-right turn, roll backwards a short distance, and stop.
Walls form a narrow path around you, with approximately **2in (5cm) on either side**.

Goal:
Move to the end of the hallway, marked by the finish line.
Avoid bumping into the walls.
Move as safely and quickly as possible.



If asked to perform this task today, could you move in this path to the end of this hallway?

○ Yes, I could do this task safely and very well.

○ Yes, I could do the task safely, but not well.

○ No, I could not do it.

Task 6 of 9 (Continued)

How confident are you that you could do this task safely and consistently today?

- ○ I am very confident.
- ○ I am only somewhat confident.
- ○ I am not confident.

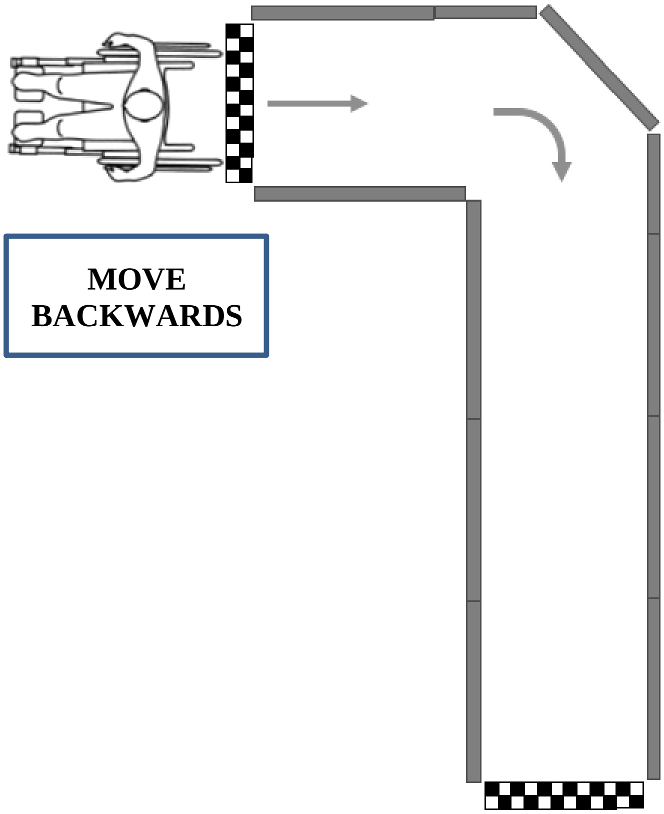
Do you expect any of the following to occur?
Please select all that apply.

- ☐ I expect to bump into a wall.
- ☐ I expect to go slowly or take a long time.
- ☐ I expect I would need to rest before I reach the finish line.
- ☐ Other, please specify: ______________________________
- ☐ No, I do not expect any of these to occur at all.

Task 7 of 9

Roll backwards, make a backwards-left turn, roll backwards a short distance, and stop.
Walls form a narrow path around you, with approximately **2in (5cm) on either side**.

Goal:
Move to the end of the hallway, marked by the finish line.
Avoid bumping into the walls.
Move as safely and quickly as possible.



If asked to perform this task today, could you move in this path to the end of this hallway?

- ○ Yes, I could do this task safely and very well.
- ○ Yes, I could do the task safely, but not well.
- ○ No, I could not do it.

Task 7 of 9 (Continued)

How confident are you that you could do this task safely and consistently today?

- ○ I am very confident.
- ○ I am only somewhat confident.
- ○ I am not confident.

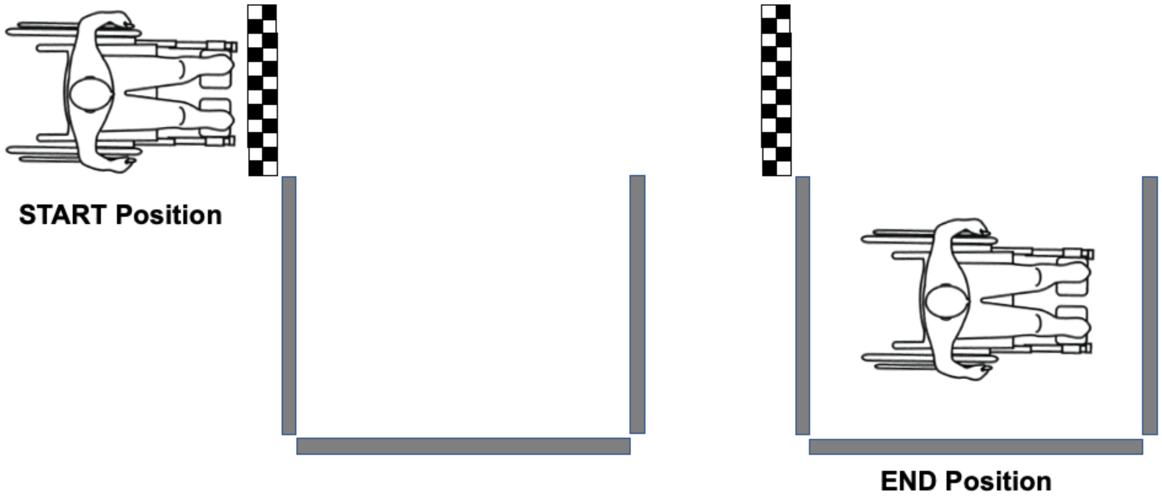
Do you expect any of the following to occur?
<u>Please select all that apply.</u>

- ☐ I expect to bump into a wall.
- ☐ I expect to go slowly or take a long time.
- ☐ I expect I would need to rest before I reach the finish line.
- ☐ Other, please specify: ____________________
- ☐ No, I do not expect any of these to occur at all.

Task 8 of 9

Roll into a parallel park.
Walls form a moderately wide parking space, with approximately **6in (15cm) in front and behind you**.

Goal:
Move from the START position into the END position.
Avoid bumping into the walls.
Move as safely and quickly as possible.



If asked to perform this task today, could you move into this parallel park?

○ Yes, I could do this task safely and very well.

○ Yes, I could do the task safely, but not well.

○ No, I could not do it.

Task 8 of 9 (Continued)

How confident are you that you could do this task safely and consistently today?

○ I am very confident.

○ I am only somewhat confident.

○ I am not confident.

Do you expect any of the following to occur?
<u>Please select all that apply.</u>

☐ I expect to bump into a wall.

☐ I expect to go slowly or take a long time.

☐ I expect I would need to rest before I reach the END position.

☐ Other, please specify: ______________________________

☐ No, I do not expect any of these to occur at all.

Task 9 of 9

Roll into a parallel park.

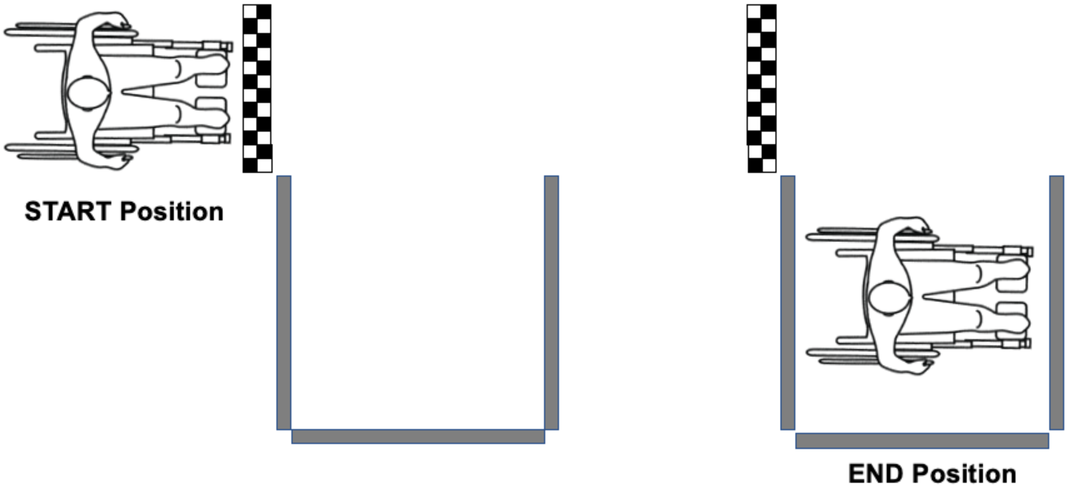
Walls form a narrowly wide parking space, with approximately **2in (5cm) in front and behind you**.

Goal:

Move from the START position into the END position.

Avoid bumping into the walls.

Move as safely and quickly as possible.



If asked to perform this task today, could you move into this parallel park?

○ Yes, I could do this task safely and very well.

○ Yes, I could do the task safely, but not well.

○ No, I could not do it.

Task 9 of 9 (Continued)

How confident are you that you could do this task safely and consistently today?

○ I am very confident.

○ I am only somewhat confident.

○ I am not confident.

Do you expect any of the following to occur?
Please select all that apply.

☐ I expect to bump into a wall.

☐ I expect to go slowly or take a long time.

☐ I expect I would need to rest before I reach the END position.

☐ Other, please specify: ____

☐ No, I do not expect any of these to occur at all.

THANK YOU FOR YOUR TIME

GIFT CARD AND CONTACT CONSENT

Please leave any questions or comments you may have.

____

____

____

To receive one $10 gift card, please provide your name, contact information, and mailing address.

Name ______________________________

Phone __________________ AND/OR Email

____

Mailing Address: ______________________________

____

____

Please consider staying in touch to hear about future studies investigating manual wheelchair usage and the potential benefits of interventions.

Your information will <u>not</u> be shared to other research groups or organizations.

☐ **Yes, I consent to being contacted directly about future studies.**

[END OF SURVEY]

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