SPATIAL DEFICITS IN VISUOMOTOR CONTROL FOLLOWING RIGHT PARIETAL INJURY

by

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Abstract

Superior parietal cortex has been implicated in visuomotor guidance and is proposed to be specialised for action in the lower visual field and peripersonal space. Two patients, one with a right superior parietal lesion leading to optic ataxia (ME), and one with a lesion affecting right inferior parietal cortex (LH), were compared to elderly controls (n=8) and young controls (n=8) on a reciprocal pointing task with movements made in the near-far direction (i.e., sagittal plane) or right-left direction (i.e., fronto-parallel plane). In contrast to both control groups, who demonstrated a speed-accuracy trade-off in movement time and peak velocity, neither of the patients did. When the time spent post-peak velocity (represented as a percentage of total movement time) was examined, both patients demonstrated larger times post-peak velocity than controls for all movement directions. Furthermore, while rightward movements of the right hand had higher times post-peak velocity than leftward movements there were no directional patterns for near-far movements which contrasted with controls who had larger times post-peak velocity for near movements. The patient with the more superior lesion (ME) had the greatest difficulty with movements made back toward the body, suggestive of a role for superior parietal cortex in the fine tuning of movements made in this region of space (i.e., personal or peripersonal space). In contrast, all directions of movement seemed to be equally affected in the patient with a more inferior lesion. These results are discussed in terms of the different roles played by inferior and superior parietal cortex in the control of visually guided movements.

Acknowledgements

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Introduction

A fundamental ability of humans involves the control of motor acts in a complex environment. For instance, in order to pick up a pen from a desk, one must first scan the local environment to visually identify and locate the pen among the clutter before then reaching out to grasp the pen (avoiding obstacles along the way). Such a grasping action requires precise scaling of the opening between thumb and forefinger in order to accurately acquire the object. Finally, a co-ordinated series of movements are required to bring the pen back toward the body in preparation for writing. Human lesion studies, functional neuroimaging studies, and monkey neurophysiology research have provided a great deal of information about the neural circuits that make this complex sequence of actions possible. Primary motor and premotor cortices receive projections from parietal cortex which provides the sensory information necessary for visuomotor transformations used in action planning and execution (Rizzolatti & Luppino, 2001). The parietal lobe itself can be broadly divided into two sections: the inferior and superior parietal lobules, separated by the intraparietal sulcus (Figure 1). While much is known about the distinct functions subserved by these regions of parietal cortex there remain many outstanding questions (for reviews, see Culham, Gallivan, Cavina-Pretesi, & Quinlan, in press; Husain & Nachev, 2007).

Damage to the left inferior parietal lobule often results in apraxia, a bilateral impairment of skilled movement affecting gestural control, imitiation, motor sequencing and the manipulation of tools (for a review, see McClain & Foundas, 2004). Because these deficits are quite dramatic, the left hemisphere has traditionally been considered dominant for movement control (e.g., Haaland, 2006). Lesions of the right hemisphere,

however, are not inconsequential for the control of visually guided actions. Damage to the right hemisphere, particularly to the parietal cortex, can cause subtle spatial movement deficits. The most common and dramatic outcome of right inferior parietal damage is a disorder known as unilateral neglect, in which patients fail to attend to or respond to stimuli on the contralesional – in this case left – side of space (for reviews, see Danckert & Ferber, 2006; Husain & Rorden, 2003). Neglect can also arise as a consequence of frontal damage (Husain & Kennard, 1996) or subcortical lesions (Damasio, Damasio, & Chui, 1980; Karnath et al., 2002), but is most commonly associated with lesions in right posterior inferior parietal cortex (e.g., Heilman, Bowers, & Watson, 1983; Leibovitch et al., 1998; Mort et al., 2003; Vallar, 2001; Vallar & Perani, 1986; although Karnath and colleagues (Karnath, Ferber, & Himmelbach, 2001; Karnath, Berger, Küker, & Rorden, 2004) argue that the critical lesion site is in the superior temporal lobe).

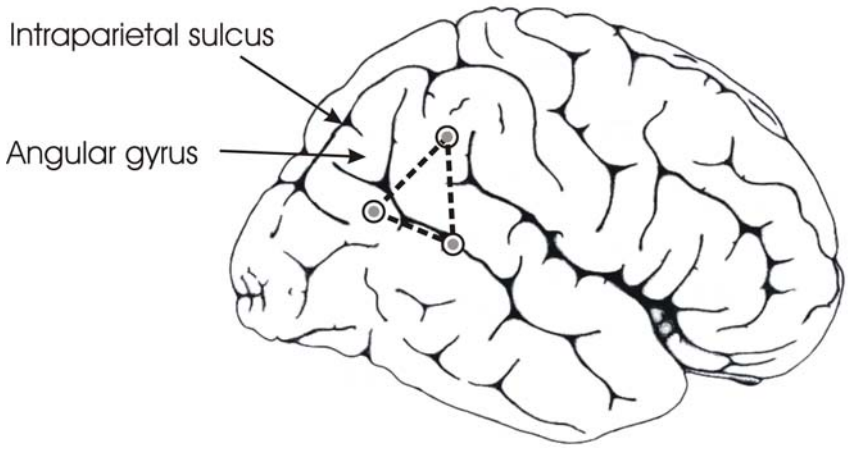

Figure 1. Parietal areas of the human brain. Superior parietal cortex is above the intraparietal sulcus. Inferior parietal cortex is the area below the intraparietal sulcus and includes the angular gyrus and the temporo-occipito-parietal junction, indicated here by the dashed lines.

In addition to the dramatic deficits of attention for the left side of space, neglect patients also demonstrate impaired movement control when directing movements to the left side of space (for a review, see Coulthard, Parton, & Husain, 2006). Studies of motor control in neglect patients have mostly looked at reaction time (RT; how long it takes to *plan and initiate* a movement) and movement time (how long it takes to *execute* the movement) for arm movements to targets presented to the right and left of the patient's body midline. While RT is generally taken to reflect the time required for movement planning, movement time reflects the time required for execution processes including the use of on-line visual and proprioceptive information to adjust the trajectory of the reach. Patients with neglect have been found to have longer reaction times when moving to the left than when moving to the right (Heilman, 1985; Husain, Mattingley, Rorden, Kennard, & Driver, 2000; Mattingley, Bradshaw, & Phillips, 1992). More variable results have been found for movement time. Heilman (1985) examined the performance of neglect patients with frontal and/or parietal damage and failed to demonstrate a directional difference in movement times (see also Karnath, Dick, & Konczak (1997)). Mattingley, Husain, Rorden, Kennard, and Driver (1998), however, found that movement times to the left were slower for the right brain damaged patients with neglect who had damage anterior to the central sulcus and/or subcortical lesions, but not for those who had damage restricted to brain areas posterior to the central sulcus and without subcortical involvement. In a follow-up to this work, Husain and colleagues required patients to execute both leftward and rightward reaches to targets in left space. For neglect patients with right parietal damage, reaction times for rightward reaches to a left target were faster than for leftward reaches to the same target. This result was not found, however, for

neglect patients with frontal damage. In contrast, movement time was greater when reaching to left targets than to right targets for the frontal neglect patients but not for the parietal neglect patients.

These studies suggest that damage to the inferior parietal lobe in neglect patients impairs the planning phase but not the execution phase of a movement. While lesions of inferior parietal cortex often lead to the neglect syndrome, more superior lesions of parietal cortex in either hemisphere tend to produce optic ataxia, a disorder primarily of motor control. The most obvious symptom of optic ataxia is misreaching to targets in peripheral vision with somewhat preserved reaching to foveated targets (Perenin & Vighetto, 1988). Optic ataxics can exhibit “field effects” in which the deficit appears when reaching into contralesional space with either hand and/or “hand effects” in which the deficit appears when reaching with the contralesional hand to either side of space (Perenin & Vighetto, 1988). When a patient demonstrates both field and hand effects, the greatest impairment occurs when the patient reaches into contralesional space with the contralesional hand (Figure 2).

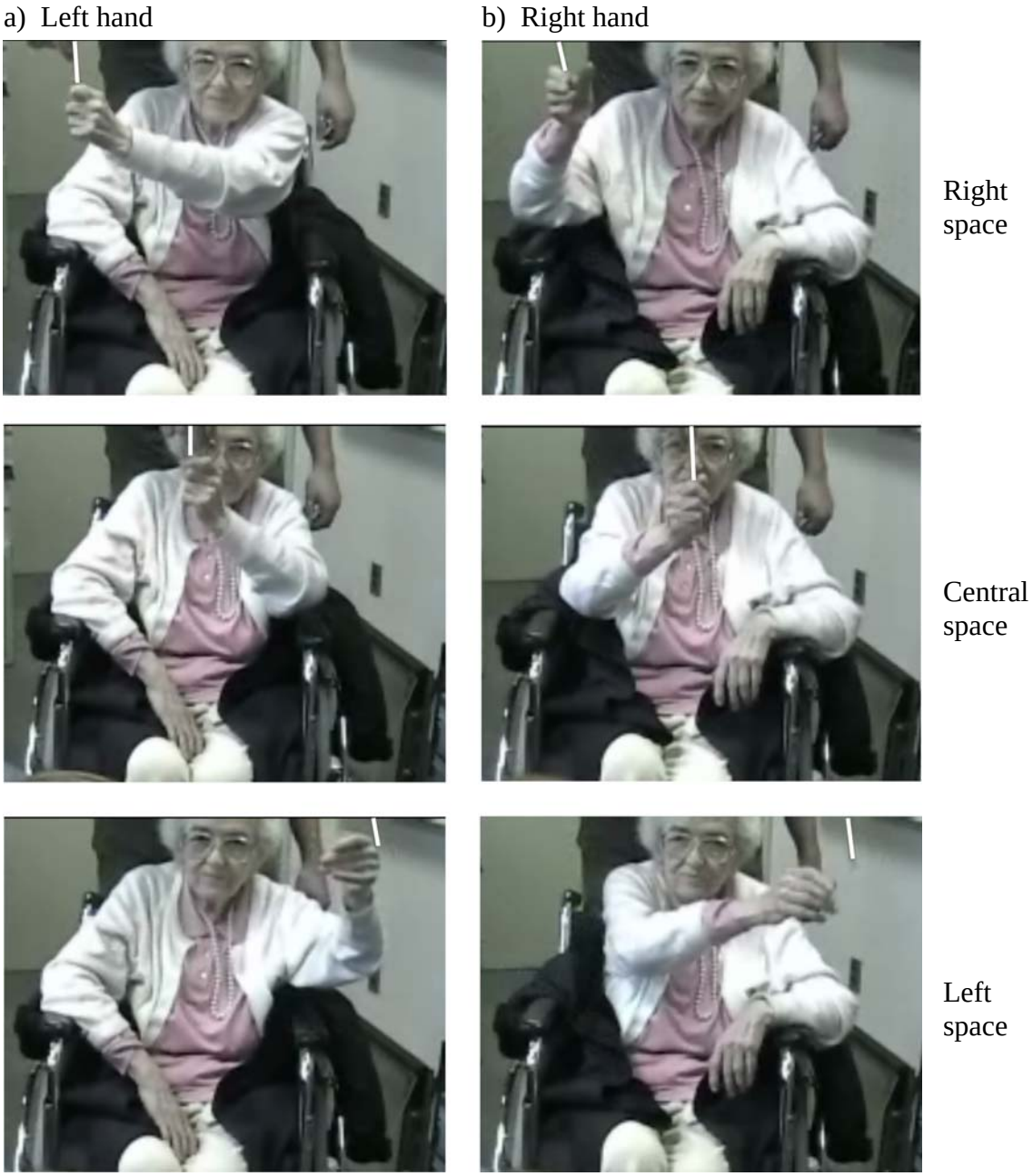

Figure 2. Optic ataxic patient ME reaching for targets. a) When ME reaches for the target with her left, ataxic hand, she acquires it easily if it is in central vision. When the target is in right peripheral vision, she again acquires it, although more hesitantly (i.e., movements are slower and less precise – this is evident in the full video of her performance). When the target is in left peripheral vision, she attempts to grasp before she has reached the target. b) When ME reaches for the target with her right, non-ataxic hand, she acquires the target easily when it is in central or right peripheral vision but again attempts to grasp the target before she has reached it when the target is in left peripheral vision.

Originally, optic ataxia was conceptualised simply as a deficit of visually guided movement when those movements were performed in peripheral vision (Bálint, 1909). Recent work, however, points to a problem with on-line movement control in optic ataxic patients that prevents them from making fast, automatic, corrections to movements (Gréa et al., 2002; Pisella et al., 2000; Rossetti et al., 2005). When a target location changes in flight, healthy individuals smoothly correct their movement path in order to reach the new target location. Optic ataxic patients, however, must initiate an entirely separate movement plan in order to acquire the new target location. Similarly, disrupting parietal activity in healthy individuals using transcranial magnetic stimulation (TMS) disrupts the ability to make on-line corrections to changes in target locations that occur in flight (Desmurget et al., 1999). Thus, one could draw a fairly crude distinction between the role played by inferior and superior regions of parietal cortex in the control of visually guided actions. That is, while inferior parietal damage (often associated with neglect) causes deficits in movement *planning* to the contralesional side (as measured by RT), superior parietal damage (often associated with optic ataxia) causes impairments during the *execution* phase of movements to contralateral space.

While work with humans has provided information about the broad roles of inferior and superior areas of parietal cortex, work on monkeys has provided more detailed analyses of the function of discrete regions within both inferior and superior parietal cortex. For example, discrete regions of the macaque parietal lobe encode spatial locations in coordinates relative to eyes, head, and limbs (Graziano & Gross, 1998). These multiple spatial reference frames and transformations between them are necessary for both planning and executing reaches to visually identified targets. In the macaque

lateral intraparietal area (LIP) salient visual stimuli are encoded in retinocentric coordinates (although there is debate in the literature about whether the activity of these neurons is coded explicitly in terms of potential targets for action intention (Snyder, Batista, & Anderson, 2000) or instead reflect processing of stimulus salience independent of any action directed toward those stimuli (Goldberg, Bisley, Powell, Gottlieb, & Kusunoki, 2002; Kusunoki, Gottlieb, & Goldberg, 2000)). The same stimuli are encoded in arm-centred co-ordinates in a neighbouring region of medial intraparietal area (MIP; Johnson, Ferraina, Bianchi, & Caminiti, 1996).

Further distinctions have been made between the macaque ventral intraparietal area (VIP), which encodes stimuli with respect to their proximity to the head, and the anterior intraparietal area (AIP), thought to be involved in preshaping the hand for grasping (see Culham, Cavina-Pratesi, & Singhal, 2006 for a review). Support for similar fine-grained distinctions in human parietal cortex has recently been found through the use of human brain imaging. An area at the junction of the anterior intraparietal sulcus and the inferior postcentral sulcus is believed to be the human homologue of macaque AIP and a region known as the parietal eye fields is thought to be the human homologue of macaque LIP (Culham et al., 2006). The search for a homologous area to macaque VIP has not produced consistent results, although several candidates have been proposed. Based on fMRI work, several areas have been proposed as the human homologue of MIP – medial intraparietal sulcus, precuneus, and the parieto-occipital junction (POJ; Culham et al., 2006). Importantly, the vast majority of the areas implicated in human visuomotor transformations of the kind needed for efficient control of reaching and grasping movements are located in superior, not inferior parietal cortex (Culham et al., 2006).

What is consistent across the different regions discussed above is the involvement of each in the utilisation of visual information for the control of actions (although see Goldberg et al., 2002; Gottlieb, 2002; Kusunoki et al., 2000). Early conceptions of the primate visual system suggested that visual information was processed in two main pathways both originating in primary visual cortex – area V1 (Ungerleider & Mishkin, 1982). The ventral stream, which runs from V1 to inferior temporal cortex, plays an important role in object recognition (i.e., the so-called "what" pathway), while the dorsal stream from V1 to posterior parietal cortex was originally thought to process the spatial layout of the environment (i.e., the so-called "where" pathway; Ungerleider & Mishkin, 1982). In part due to the neurophysiological findings discussed above implicating dorsal parietal cortex in the control of visually guided actions, together with findings from human neuropsychology, more recent conceptualisation of these two systems has recast the dorsal stream in terms of "how" visual information is used to control visually guided actions (Goodale & Milner, 1992; Milner & Goodale, 1995). Superior parietal cortex has traditionally been considered part of this dorsal stream. The association of neglect and motor planning deficits with inferior parietal lobe lesions, however, suggests that there may be a third pathway in which visual information is decoded for the purposes of action control which runs through inferior parietal cortex and is important for movement planning (Coello, Danckert, Blangero, & Rossetti, 2007).

Previc (1990, 1998) has argued that the dorsal "how" pathway is specialised not only for visually guided actions but also for the processing of visual information in peripersonal space – space near the body, within arm's reach – and the lower visual field (LoVF). Macaque and human studies have found an over-representation of the lower

LoVF in retinal ganglion cells (Curcio & Allen, 1990), while area V6A of the macaque includes neurons whose receptive fields typically include more of the lower than the upper visual field (Galletti, Fattori, Gamberini, & Kutz, 1999). This region (V6A) is also considered part of the dorsal stream and has been shown to be selective for reaching movements in the macaque (Galletti, Fattori, Kutz, & Battaglini, 1997). It is not currently known whether or not human superior parietal cortex maintains representations of both the upper and lower visual fields that mirror those observed in the macaque (Danckert & Goodale, 2003). Recent human studies, however, have provided some evidence for a functional advantage in the LoVF for visually guided actions (for a review, see Danckert & Goodale, 2003). Pointing to targets in the LoVF has been shown to be faster and more accurate than pointing to targets in the upper visual field (UpVF; Danckert & Goodale, 2001) and late stage movement trajectories have been demonstrated to be more consistent in the LoVF than in the UpVF (Khan & Lawrence, 2005; although not all studies have found a LoVF advantage for action control, e.g., Binstead & Heath, 2005). Finally, neuroimaging has revealed increased activity in left inferior parietal cortex when perceptual and motor tasks are performed on stimuli presented in peripersonal versus extrapersonal space (Weiss, Marshall, Zilles, & Fink, 2003).

It seems clear, then, that superior parietal areas play an important role in controlling movements in peripersonal space and the LoVF. Many studies, however, have found that neglect patients, who typically have more inferior parietal lesions, exhibit more neglect in peripersonal space (Butter, Evans, Kirsch, & Kewman, 1989; Cowey, Small, & Ellis, 1999; Guariglia & Antonucci, 1992; Halligan & Marshall, 1989; Kageyama, Imagase, Okubo, & Takayama, 1994; Làdavas, Carletti, & Gori, 1994*;*

Mennemeier, Wertman, & Heilman, 1992; Pitzalis, Spinelli, & Zoccolotti, 1997; Rapcsak, Cimino, & Heilman, 1988; Shelton, Bowers, & Heilman, 1990). It is possible that neglect patients have deficits in the LoVF and peripersonal space as a consequence of loss of input from the superior parietal cortex. No studies, however, have directly compared the behavioural consequences of inferior and superior parietal lesions on tasks that test performance in the LoVF or peripersonal space.

Visually guided actions may have an advantage in the LoVF due to improved use of visual feedback in that region of space. Lesions to superior parietal cortex causing optic ataxia may disrupt the areas that encode coordinates in different reference frames and/or the areas that transform coordinates from one reference frame to another (Khan & Lawrence, 2005). A transformation deficit of this kind should also lead to impaired use of visual feedback. Superior parietal lesions, then, might be expected to affect actions in the LoVF disproportionately. In other words, optic ataxia patients with superior parietal lesions would be expected to be impaired when executing actions in the LoVF or peripersonal space. To our knowledge, no motor control studies of patients with optic ataxia, however, have compared reaches toward the body (i.e., toward peripersonal space) to reaches made away from the body (i.e., toward extrapersonal space).

The current study compares the kinematics of reaches of a patient with optic ataxia to those of a patient with right brain damage but no optic ataxia and those of young and elderly healthy controls. Due to the patients' ages (88 and 52 years old), the most appropriate comparison group is the elderly controls. Nevertheless, both young and elderly controls participated so that any effects in this task due solely to aging could be identified. Older participants typically show longer movement times and lower peak

velocities than younger participants (see Krampe, 2002, for a review) Furthermore, manual asymmetries typically found in young participants have been found to be reduced in elderly participants (Francis & Spirduso, 2000; Kalisch, Wilimzig, Kleibel, Tegenthoff, & Dinse, 2006). Participants pointed toward targets in left and right space, as well as targets presented closer to and further away from the body. This allowed a direct comparison to be made of leftward and rightward movements, as well as movements toward and away from the body. Impaired performance in the patient with optic ataxia for reaches made toward the body relative to reaches away from the body was expected and would support the hypothesis that superior parietal cortex is specialised for movements in peripersonal space.

Method

Overview

The current study set out to investigate motor control in two patients with right parietal damage due to stroke, a group of elderly controls, and a group of young controls, and to compare the performance of the patients directly to the elderly controls. The continuous pointing task explicitly involved a speed-accuracy trade-off component. Each trial consisted of a series of visually guided reach-to-point movements to targets presented on a table in front of the participant. Target size varied between trials. One patient (ME) presented with optic ataxia at the time of testing and the other patient (LH) initially presented with mild neglect that had resolved by the time of testing.

Participants executed sequential movements toward targets in left and right space, as well as targets aligned with the body midline and placed near the body, far from the

body (just within reach), or midway between the two. This allowed comparisons of movements toward and away from the body, as well as movements toward left and right space. Left-right movements and near-far movements were performed on separate intermixed trials with a new random order for each participant.

Participants

Two patients with right hemisphere brain damage, a group of undergraduates, and a group of senior citizens were tested. Eight young undergraduates (6 male) from the University of Waterloo (mean age 21.1 years, sd 2.9) and 8 elderly people (2 male; mean age 72.1 years, sd 9.3) from the Waterloo Research in Aging Pool participated in the study. All control participants were right-handed and free of brain injury, neuropsychological conditions, and mental illness. Aside from these 16 control participants, three elderly participants and one young participant were excluded from the analyses because of missing data due to equipment difficulties. A further two younger participants were removed from the analyses due to the absence of any discernible minima between their first and third pointing movements.

Patient ME was an 88 year old female who suffered a haemorrhagic stroke affecting her right superior parietal cortex, extending slightly below the intraparietal sulcus into the inferior parietal lobe (Figure 3). On initial examination ME presented with very mild neglect that had completely resolved prior to her participation in this study. ME was tested nine months after her stroke, at which time she demonstrated good use of both her upper limbs in terms of gross and fine motor control.

ME did demonstrate optic ataxia at the time of testing. Optic ataxia was assessed by having the patient fixate centrally with her head, trunk, and eyes aligned straight-

ahead. An experimenter stood behind the patient and placed a pen in either her peripheral visual field (left or right side of space) or in central vision. The patient was asked to reach out and grasp the object with either her left or right hand while maintaining fixation (Perenin & Vighetto, 1988). ME demonstrated large errors when reaching to grasp targets in her left periphery that were evident when using either her left or right hand. She had no obvious problems, however, with targets in central vision. When the target was placed in her right peripheral field, errors were only evident when she attempted to grasp the target with her left – contralesional – hand (Figure 2).

Patient LH was a 52 year old male who suffered a right hemisphere haemorrhagic stroke extending from frontal to parietal cortices (Figure 4). Importantly, the superior parietal cortex appeared to be spared in this patient. LH was tested 10 months post-stroke. In the acute stages post-stroke, LH showed some signs of mild neglect, however his performance on clinical measures of neglect were normal by the time of testing. LH did not show any signs of optic ataxia. At the time of testing, LH's left limbs were hemiparetic, therefore he used only his right, ipsilesional hand in the current study.

Lesion overlay analysis was conducted for each patient. Lesion data were analysed using the protocol outlined by Ferber and Danckert (2006). All lesions (defined as the hypointense or hypodense tissue compared to its surrounding parenchyma) were traced on CT scans on a slice-by-slice basis using ANALYZE 7.0 AVW™ Software (Biomedical Imaging Resource, Mayo Foundation, Rochester, MN; Robb, 2001; Robb & Barillot, 1989; Robb, Hanson, Karwoski, Larson, Workman, & Stacy, 1989). All scans were then transferred to the ICBM152 template from the Montreal Neurological Institute (http://www.bic.mni.mcgill.ca/cgi/icbm_view), based on the average of 152 normal MRI

scans approximately matched to Talairach space. This transformation was a two-step process using Automatic Image Registration version 5.2.5 software (AIR; http://bishopw.loni.ucla.edu/AIR5): the first step was a spatial normalization protocol including a linear 12-parameter affine transformation (including aligning scans to ACPC aligned Talairach space; Talairach & Tournoux, 1988). The second step was a non-linear fourth order parameter warping model to make scans fit best to the template. The resulting images had a voxel size of 1mm × 1mm × 1mm. Using the transformed lesion maps, the proportion of each Brodmann area or anatomical region involved in each patient's lesion was estimated using the "broadmann" and "AAL" templates in MRIcro (http://people.cas.sc.edu/rorden/). To then superimpose the individual brain lesion maps, the template "ch2" in MRIcro was used (Rorden & Brett, 2000).

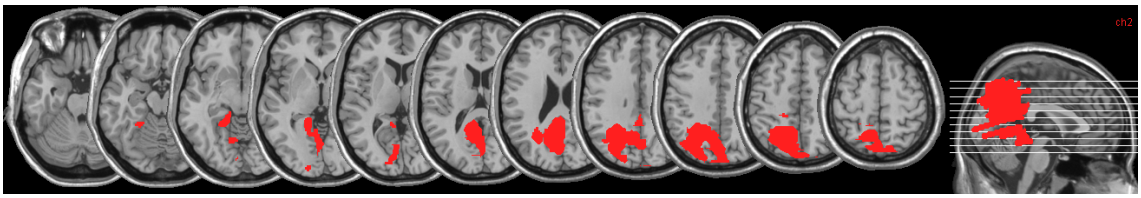

Figure 3. CT images for patient ME overlaid on a standard brain.

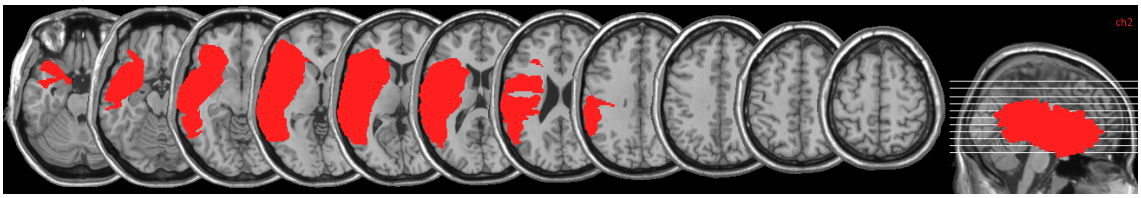

Figure 4. CT images for patient LH overlaid on a standard brain.

Apparatus and Procedure

The targets for pointing movements were white wooden blocks with four possible target sizes of 2, 3, 4, or 5 cm square. Each target was 2 cm in height. Three blocks of the same size were attached to one of four black wooden boards, each 20 cm wide and 73 cm long. The blocks were placed such that the centres of adjacent blocks were 20 cm apart. For each trial, one of the boards was placed on a black table either with the targets aligned in the fronto-parallel plane in order to examine left-right movements or perpendicular to the body in order to examine near-far movements (Figure 5). A piece of tape attached to the table indicated the resting position of the index finger between trials. The board was placed on the table such that the centre block was always 30 cm away from the resting position.

Participants rested the index finger of the hand being tested on the starting position and waited for a verbal cue that would inform them which target would be the starting point for a given trial. Participants were instructed to begin pointing with their first movement made to one of four possible targets: the left target, the right target, the nearest target, or the farthest target. The corresponding verbal cues were “Start left,” “Start right”, “Start near”, and “Start far”. After the verbal cue, the experimenter signalled the participant to start the movement by saying “Go”. In each trial, the participant moved from the start position to the cued first target, then to the centre target, then continued in the same direction to touch the next target, then made pointing movements back to the centre target, then back to the cued first target, and finally back to the start position.

Each participant completed 80 trials with each hand, which provided five trials for each combination of start position and target size. Which hand was tested first was counterbalanced across participants in each group. Patient LH was unable to use his left hand so data was collected only for his right hand. For control participants, trial order was randomised across the 80 trials for each hand. For patients, trial order was randomised within each block of twenty trials to allow for testing across multiple sessions if needed. Patient ME was tested in two sessions separated by one week, but she completed all the trials for one hand in each session. All other participants completed all trials in one session.

Data Collection and Processing

Kinematic data were collected using the Northern Digital Optotrak system, which uses infrared-sensitive cameras and infrared-emitting diodes (IREDs) to track movement. One IRED was taped to the styloid process of the wrist and another to the index finger where the nail meets the skin on the outside of the finger. Data was collected at 250 Hz. A calibration file was created for each participant for each hand. The calibration file was used to convert the recorded position data into xyz coordinates with the origin at the left corner of the table closest to the participant.

Each trial consisted of a six part movement sequence. After excluding movements to and from the start position to the first target, each trial then provided data for two movements in one direction and two movements in the opposite direction (Figure 6). Only the portion of the movement from when participants touched the first target the first time until they touched the first target the second time was included in the analyses. That is, movements from the starting point to and from the first target were excluded.

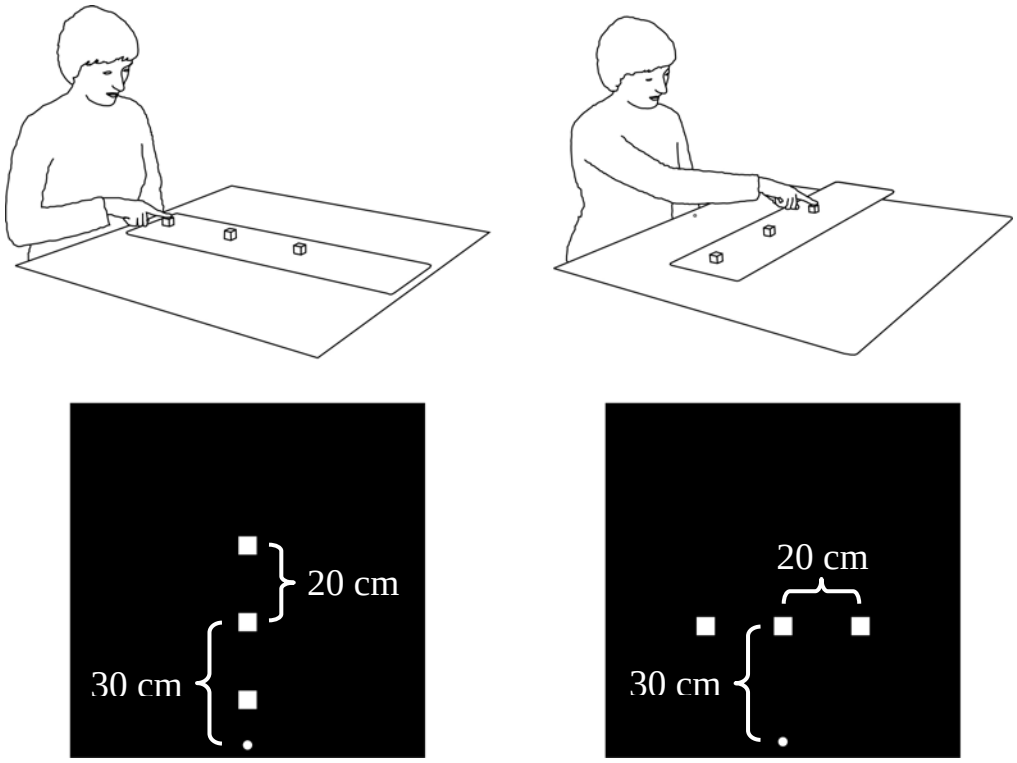

Figure 5. Eye-level and overhead views of the two possible table configurations. The circle represents the resting location. Each square represents a target. a) The targets were placed along a near-far axis aligned with the body midline of the participant. b) The targets were placed along a fronto-parallel axis in front of the participant.

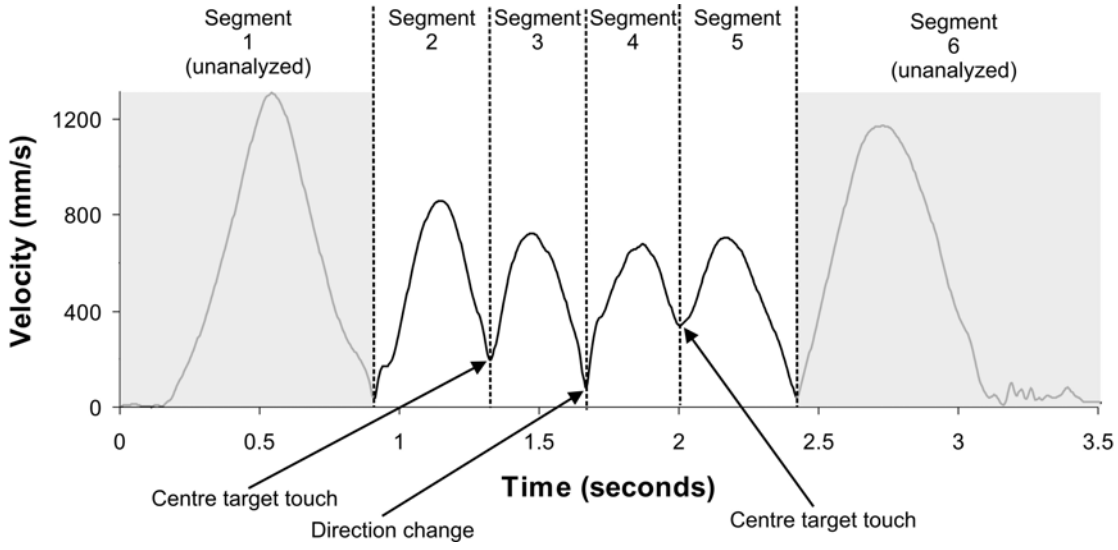

Figure 6. Sample velocity profile indicating segments of the movement sequence.

Filtering, interpolating, differentiating, and producing resultant velocity traces were performed using the Kinanalysis program. Data were subjected to a 15 Hz Butterworth filter. All missing frames were interpolated and missing frame data was recorded for later comparison with selected critical frames. Position data were differentiated to create vector specific velocity traces for the x, y and z direction and these individual velocity traces were combined to create a resultant velocity trace for each trial.

The start of each movement was defined as the first frame in which resultant velocity was greater than 50 mm/second for 10 consecutive time points. When the first recorded frame fit this definition, the beginning of the first movement was denoted as missing. Using this criterion, the first movement segment (from the starting point to the first target) was missing in 21% of trials for the Young group, 34% of trials for the Old group, and 90% of trials for the patients. The end of each movement was defined as the trough in resultant velocity at the end of segment 6, when the participant moved from the final target back to the start position (Figure 6). Because the first movement segment was missing for so many trials, total movement time for the speed-accuracy tradeoff analysis was calculated using segments 2-5 only.

For segments 2-5, the beginning, peak velocity, and end frames for each individual movement in the sequence were determined by inspecting local minima and maxima. The selection of minima and maxima was partially automated by a computer program written in SPSS Sax Basic and were later confirmed or corrected after manual inspection of velocity traces produced by Kinanalysis.

Each selected frame was then compared to the list of missing frames for each trial. If any selected frame was within five frames of a missing frame, the selected frame and any movement it was part of was also marked as missing and removed from further analysis. 1.4% of movement segments were removed for the Young group, 2.9% for the Old group, and 1.7% for the patients.

Dependent Measures

Movement time is typically defined as the time from the beginning of the movement sequence to the end of the movement sequence. Because many beginning and ending frames were missing from our patient data, however, movement time was calculated here as the time from when the participant left the first target (which is the beginning of the second movement in the sequence) to when the participant reached the final target (which is the end of the fifth movement in the sequence; Figure 6). Movement time for a trial was used to determine the presence of a speed-accuracy trade-off. Mean peak velocity for the whole movement sequence from the first to the final target was also inspected for speed-accuracy trade-offs. Mean peak velocities for movement segments 2-5 were also analyzed with factors of Group, Direction, Hand, and Target Size. Finally, the ratio of time after peak velocity to the total time of the movement segment (here termed “time post-peak velocity”) was analyzed with factors of Group, Direction, Hand, and Target Size.

Results

Speed-accuracy Trade-offs

Both total movement time and peak velocity were analyzed to confirm that all participants demonstrated the expected speed-accuracy trade-off in each task. Dependent measures were calculated on a trial by trial basis and so the speed-accuracy trade-off analyses do not compare near movements to far movements or rightward movements to leftward movements. Total movement time was defined as the time between when the participant lifted their finger from the first target and when the participant touched the final target (see Figure 6 and Methods). Peak velocity was defined as the mean velocity of the four peaks that occurred between when the participant left the initial target and when they reached the final target. Separate ANOVAs were performed for the young and elderly control groups for the left-right and near-far directions of movement with within-participant factors of Hand and Target Size. Repeated measures ANOVAs were also performed for each individual patient by matching the dependent variable values by order of execution for each condition. For instance, the first left-right movement with Target Size equal to 2 cm that used the right hand was paired with the first instance of each other combination of conditions, and so on.

Young Controls

Total movement time. For left-right movements ANOVA revealed a main effect of Target Size ($F(3, 21)=8.96$, $p=.001$) which was characterised by a significant linear trend such that movement time increased as target size decreased ($F(1, 7)=12.45$, $p=.01$). The same analysis for near-far movements approached significance in the ANOVA ($F(1.3, 9.13)=4.389$, $p=.058$), while trend analysis revealed a significant linear trend such that

MT increased as target size decreased (F(1, 7)=6.56, p=.037). In addition, for near-far movements there was a main effect of Hand (F(1, 7)=5.63, p=.049) such that the right hand was faster than the left (1515 ms vs. 1622 ms for right and left hand movements respectively). No interactions were significant for either direction of movement (Figure 7).

Peak velocity. For left-right movements, ANOVA revealed main effects of Target Size (F(1.56, 10.95[1])=7.89, p=.01) and Hand (F(1, 7)=6.05, p=.044), as well as a Hand x Target Size interaction (F(3, 21)=3.46, p=.039). When examined further, both the right and left hands demonstrated significant effects of Target Size (for the right hand: F(3, 21)=6.27, p=.003; for the left hand (F(3,21)=7.63, p=.001). Trend analysis showed a significant linear trend for the right hand such that peak velocity increased as target size increased (F(1,7)=8.51, p=.022). Trend analysis for the left hand showed both a linear (F(1,7)=8.64, p=.022) and a quadratic trend (F(1,7)=16.08, p=.005), indicating that peak velocity increased as target size increased as it did for the right hand but reached an asymptote at an earlier point. In other words, the left hand showed no further increase in velocity when the target sizes of 4 and 5 cm were contrasted (Figure 8). Overall, the right hand produced higher peak velocities than the left hand (709 mm/s vs. 660 mm/s). Near-far movements only showed a main effect of Target Size (F(3, 21)=6.60, p=.003; linear trend F(1,7)=10.06, p=.016) such that peak velocity increased as target size increased in a comparable manner for both the left and right hands.

Elderly Controls

Total movement time. ANOVA indicated a main effect of and a linear trend for Target Size for both left-right (F(3, 21)=9.32, p<.001; linear trend F(3, 21)=13.9, p=.007)

[1] The Greenhouse-Geisser correction was used when the homogeneity of variance assumption was not met.

and near-far ($F(3, 21)=9.80$, $p<.001$; linear trend $F(3,21)=27.48$, $p=.001$) movements (Figure 7). No effect of Hand was found for either direction of movement and the two-way interaction was not significant for either direction of movement.

Peak velocity. ANOVA showed an effect of Target Size on peak velocity only for left-right movements ($F(3, 21)=6.96$, $p=.002$; Figure 8). There was no main effect of Hand for either direction of movement, however, there was a Hand by Target Size interaction for near-far ($F(3, 21)=5.85$, $p=.005$) but not left-right movements. Separate ANOVAs for the right and left hand for near-far movements showed that there was an effect of Target Size ($F(3, 21)=4.56$, $p=.013$) and a linear trend ($F(1,7)=8.51$, $p=.022$) for the right hand such that peak velocity decreased as target size increased. There was no effect of Target Size for the left hand.

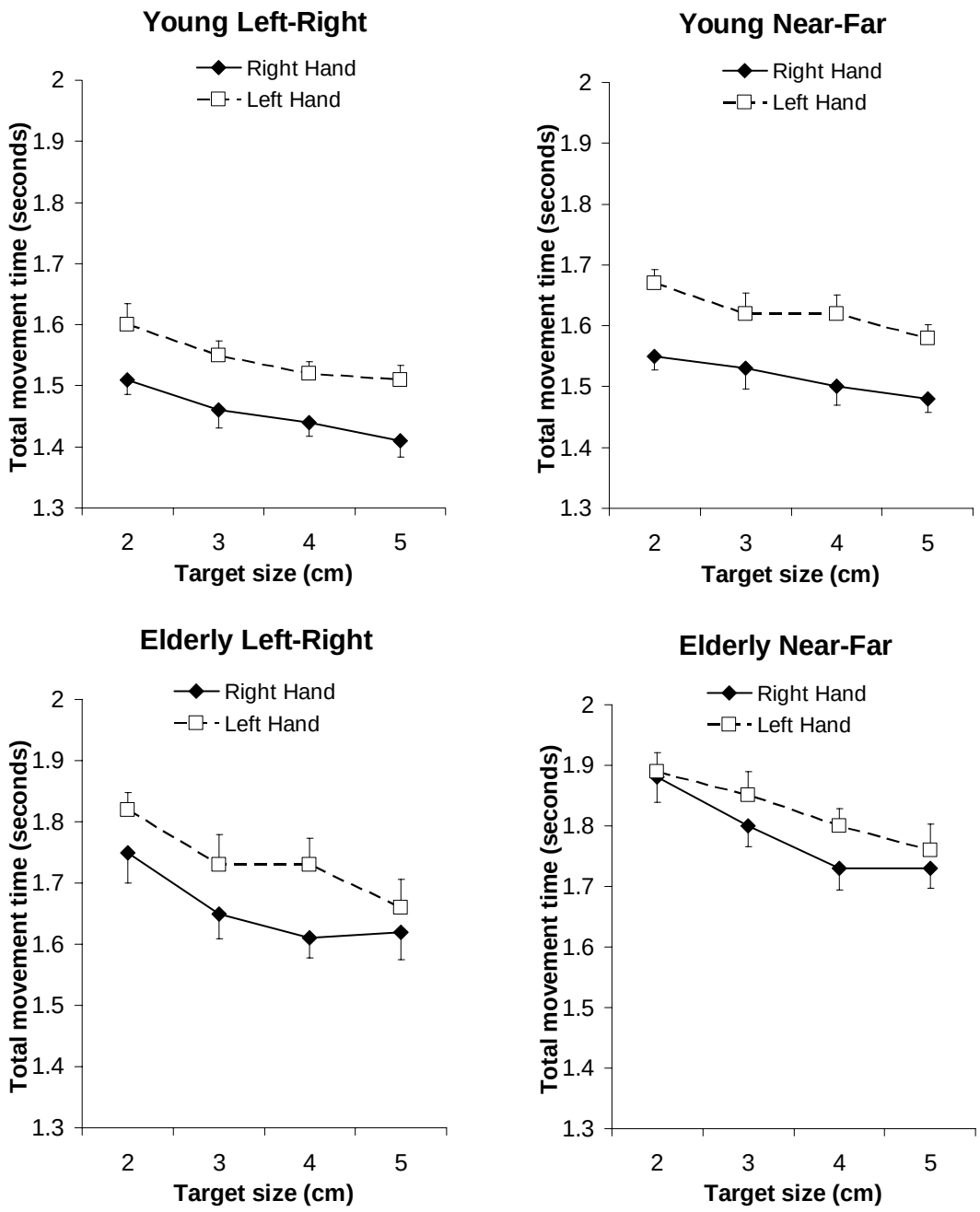

Figure 7. Speed-accuracy trade-offs in movement time by hand for each group and axis of movement. Error bars represent within-participant standard error.

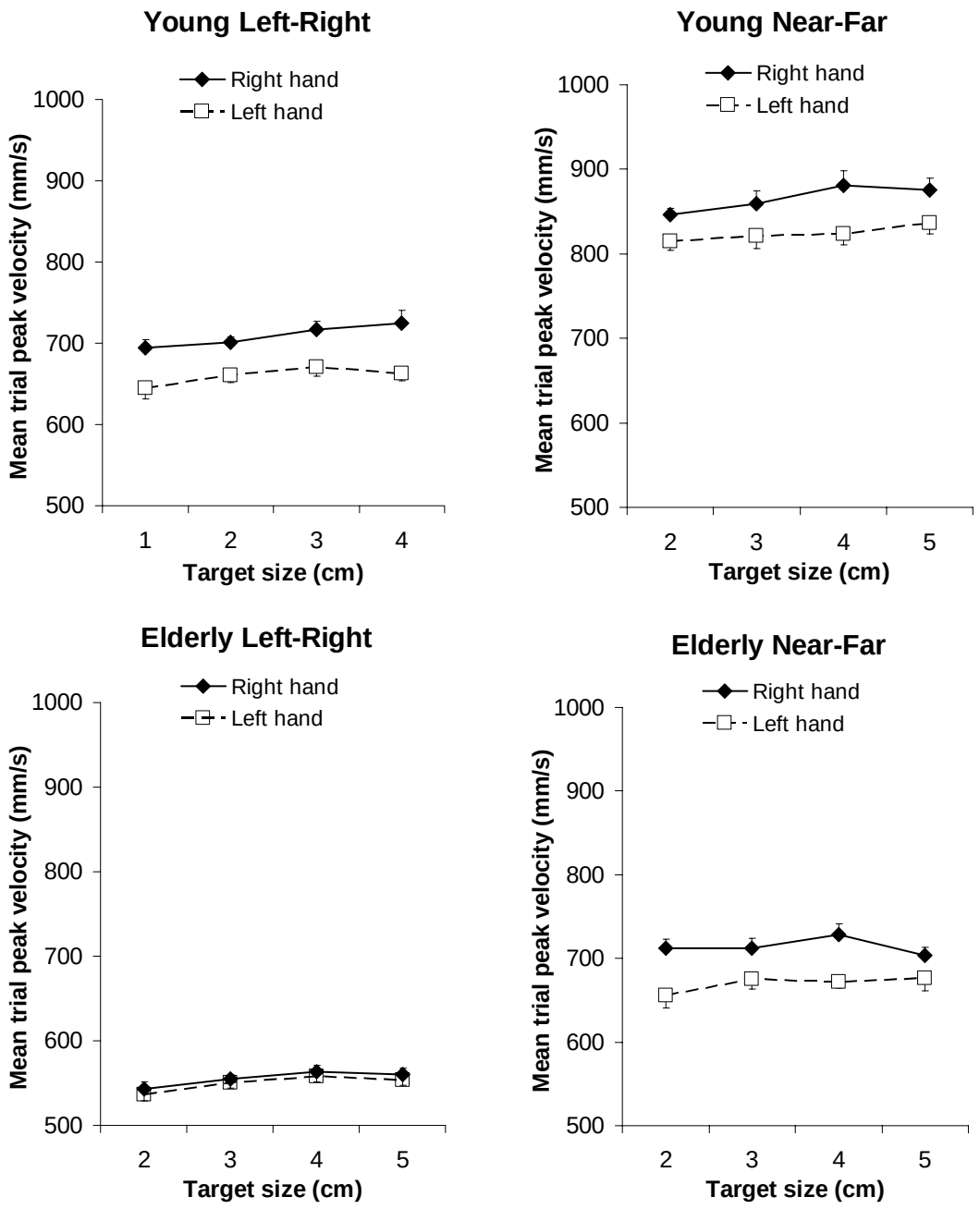

Figure 8. Speed-accuracy trade-offs in mean trial peak velocity by hand for each group and axis of movement. Error bars represent within-participant standard error.

ME

Total movement time. Repeated measures ANOVAs did not reveal any significant main effects or interactions for ME in either left-right or near-far directions of movement (Figure 9). In other words, ME failed to demonstrate the expected speed-accuracy trade-off for either directions of movement.

Peak velocity. For left-right movements, ME showed a significant effect of hand ($F(1, 9)=27.78$, $p=.001$) such that peak velocities of the left hand were higher than those of the right hand (500 ms vs. 463 ms for left and right hands respectively). ME also demonstrated a significant effect of Target Size ($F(2.179, 19.615)=3.60$, $p=.043$) with no interaction between Hand and Target Size. Further analysis of the main effect of Target Size showed a significant quadratic trend ($F(1,9)=5.88$, $p=.038$) such that peak velocities were highest for the intermediate target sizes (Figure 10). No significant effects were found for ME's near-far movements.

LH

LH did not show any significant effects on total movement time or peak velocity for left-right or near-far movements.

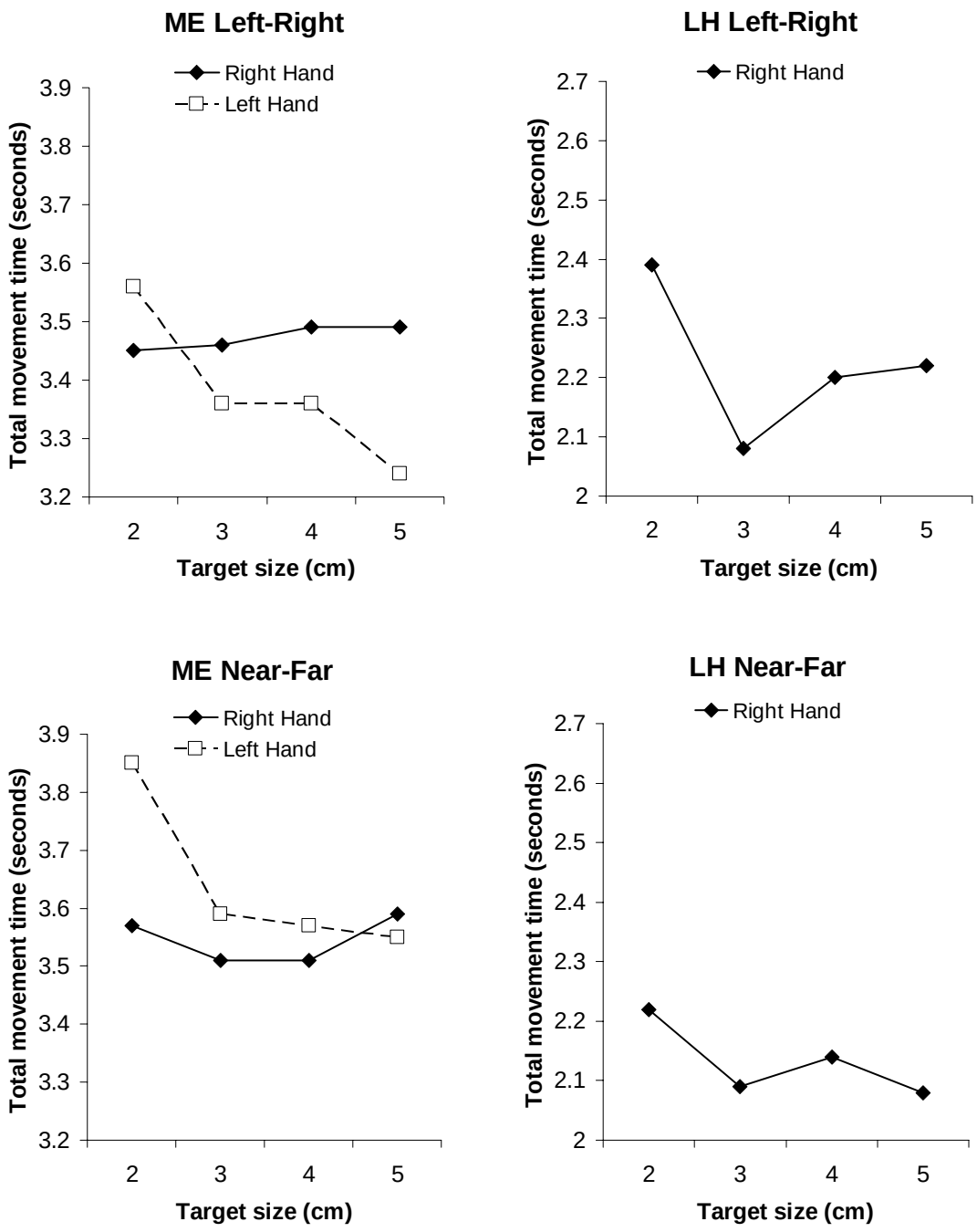

Figure 9. Speed-accuracy trade-offs in movement time by hand for each patient and axis of movement.

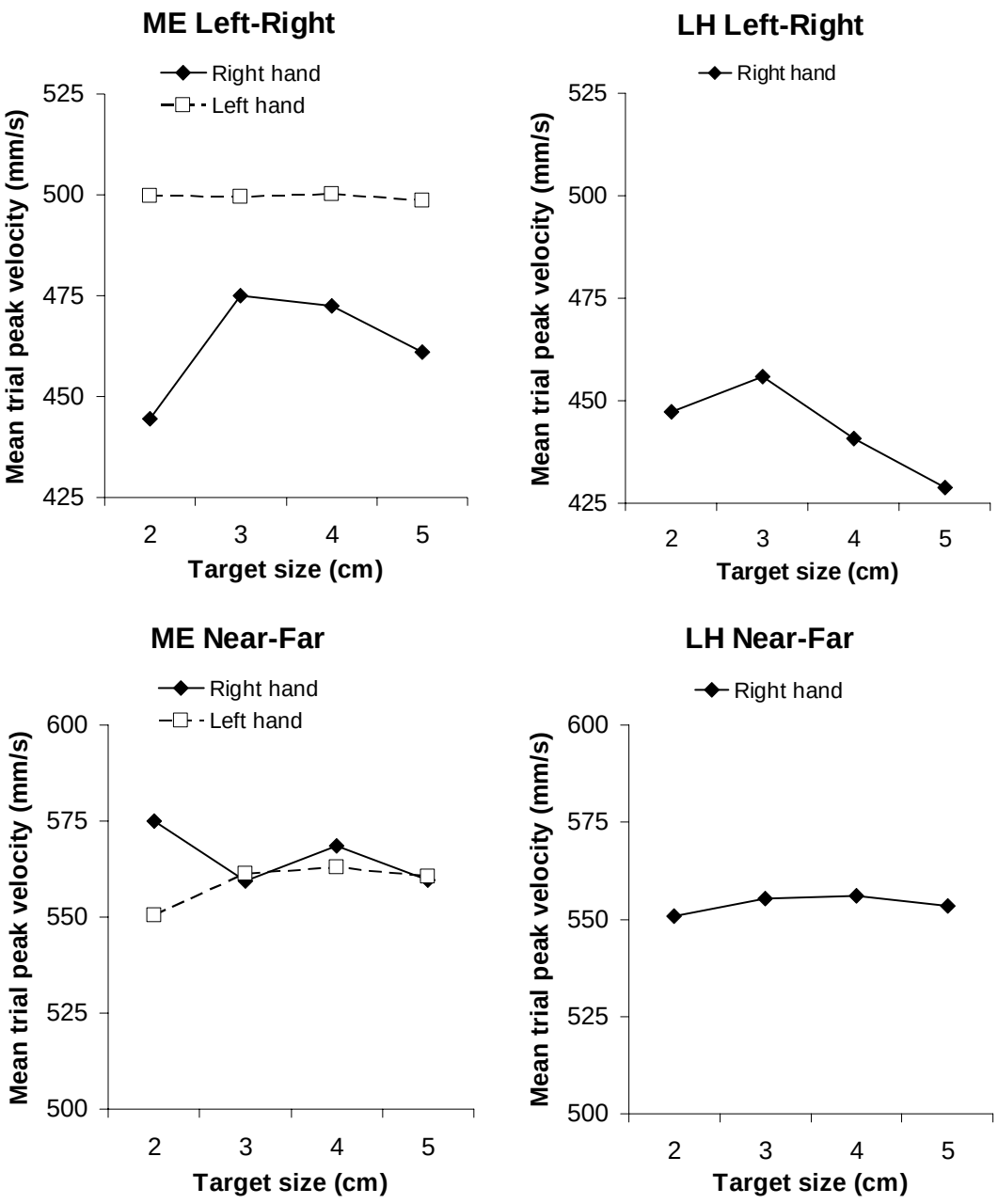

Figure 10. Speed-accuracy trade-offs in mean trial peak velocity by hand for each patient and axis of movement.

Directional Differences

Repeated measures ANOVAs were conducted for each group and each direction of movement separately with factors of Target Size, Hand, and Direction of movement. Unlike the speed-accuracy trade-off analyses, dependent variables were based on movement segments instead of individual trials. Each trial consisted of four movements between targets, two in each direction. That is, when performing a trial in the left-right direction, a participant would make two movements toward the right and two movements toward the left. In the preceding analysis we calculated average movement time and peak velocity for all of the four analyzed movement segments within a given trial, collapsing over movements toward right and left targets (or over movements toward near and far targets). For the following analyses more explicit measures of the directional components of the movements within a trial were desired. Thus, for any given trial, the two values for the same direction of movement were averaged within each trial and then averaged over all trials with the same target size for that participant. Repeated measures ANOVAs were also performed for each individual patient in the same fashion as the speed-accuracy trade-off analyses.

Two dependent measures were used: peak velocity and time post-peak velocity. The time spent slowing down before contacting a target in a pointing movement can be taken as an index of difficulty: the more difficult it is to accurately acquire the target, the longer the time spent slowing down before making contact. It is during this phase of the movement that feedback processing occurs and is used for on-line control of the reach in order to acquire the target. More time in this phase may reflect either more corrections of the movement (e.g., when the target is smaller) or may reflect more time needed to make

the same number of movement corrections. The duration of this phase was measured by taking the time from peak velocity to target acquisition. We measured this time for each individual movement segment within a trial and then expressed the time post-peak velocity as a percentage of the total movement time for that particular movement segment.

Young Controls

Peak velocity. For left-right movements (Table 1), ANOVA showed main effects of Hand ($F(1,7)=5.996$, $p=.044$) and Target Size ($F(1.58, 11.07)=8.5$, $p=.008$), as well as all possible two-way interactions: Hand x Target Size ($F(3, 21)=3.63$, $p=.03$), Direction x Target Size ($F(3, 21)=4.26$, $p=.006$), and Hand x Direction ($F(1, 7)=14.64$, $p=.006$). Hand x Direction was a crossover interaction such that peak velocities were higher for rightward movements ($t(7)=3.34$, $p=.012$) when the right hand was used (727 mm/s vs. 690 mm/s for rightward versus leftward movements respectively) but were higher for leftward movements when the left hand was used ($t(7)=3.15$, $p=.016$; 680 mm/s vs. 640 mm/s for leftward versus rightward movements respectively; Figure 11). Further analysis of the Hand x Target Size interaction found that Target Size was significant for both hands (right hand: $F(3, 21)=6.95$, $p=.002$; left hand: $F(3,21)=7.63$, $p=.001$). Trend analysis for right hand movements indicated a significant linear trend ($F(1,7)=9.46$, $p=.018$), while for the left hand, analysis indicated both a significant linear ($F(1,7)=8.64$, $p=.022$) and quadratic trend ($F(1,7)=16.081$, $p=.005$), indicating that peak velocity increased as target size increased as it did for the right hand but reached an asymptote earlier.

The Direction x Target Size interaction was also driven by different trends. Target Size showed a significant effect for both rightward ($F(1,7)=24.06$, $p=.002$) and leftward ($F(1,7)=8.04$, $p=.001$) movements. Rightward movements exhibited significant linear ($F(1,7)=7.94$, $p=.026$) and quadratic ($F(1,7)=9.63$, $p=.017$) trends while only the linear trend ($F(1,7)=10.21$, $p=.015$) was significant for leftward movements, indicating that for both rightward and leftward movements, peak velocity increased as target size increased but for rightward movements, peak velocity reached an asymptote earlier than for leftward movements.

Table 1. Mean peak velocities (mm/s; ± SD) as a function of direction, hand, and target size for left-right movements of healthy controls.

Young Controls								
	Rightward Movements				Leftward Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	711 (111)	725 (115)	733 (123)	740 (119)	674 (112)	677 (110)	700 (117)	711 (127)
Left Hand	627 (95)	644 (95)	650 (98)	638 (93)	662 (121)	678 (124)	693 (127)	687 (127)
Elderly Controls								
	Rightward Movements				Leftward Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	549 (50)	556 (46)	563 (60)	566 (62)	537 (62)	554 (57)	565 (67)	554 (73)
Left Hand	534 (43)	547 (48)	557 (56)	550 (55)	537 (33)	553 (38)	559 (46)	557 (44)

For near-far movements (Table 2), peak velocities showed main effects of Direction ($F(1, 7)=28.66$, $p=.001$) and Target Size ($F(3, 21)$, $p=.005$), both of which were qualified by a three-way interaction of Hand, Target Size, and Direction ($F(3, 21)=3.59$,

p=.031). Separate ANOVAs for each direction of movement showed that the Hand x Target Size interaction was significant for far movements (F(3, 21)=3.12, p=.048) but not for near movements. Further separate ANOVAs for each hand for far movements only showed that Target Size was significant for the right hand (F(3, 21)=3.93, p=..023) but not the left hand. Paired comparisons of peak velocity for all pairs of target sizes found no significant difference after a Bonferroni correction for multiple comparisons.

Table 2. Mean peak velocities (mm/s; ± SD) as a function of direction, hand, and target size for near-far movements of healthy controls.

Young Controls								
	Near Movements				Far Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	872 (164)	892 (190)	903 (199)	902 (182)	832 (147)	829 (148)	859 (169)	847 (164)
Left Hand	840 (152)	848 (140)	858 (149)	867 (153)	790 (122)	795 (117)	788 (125)	806 (132)
Elderly Controls								
	Near Movements				Far Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	741 (61)	737 (80)	757 (82)	734 (72)	682 (75)	690 (82)	702 (84)	677 (84)
Left Hand	667 (48)	684 (63)	686 (62)	690 (81)	648 (66)	665 (73)	662 (71)	663 (84)

Time post-peak velocity. There were no significant main effects or interactions for left-right movements (Table 3). For near-far movements (Table 4), ANOVA showed a main effect of Direction (F(1,7)=17.97, p=.004) qualified by a Target Size x Direction interaction (F(3, 21)=5.23, p=.007). Overall, young controls spent a higher proportion of time post-peak velocity for near movements than far movements (.540 vs. .505). Separate

ANOVAs for each direction did not reveal a significant effect of Target Size for either near or far movements but pairwise comparisons of near and far time post-peak velocity at each Target Size (with a Bonferroni correction for multiple comparisons) found significant differences between the 2 cm (near 54.5%, far 50.0%; $t(7)=4.79$, $p=.002$), 3 cm (near 54.2%, far 50.5%; $t(7)=3.92$, $p=.006$), and 4 cm targets (near 53.7%, far 50.7%; $t(7)=4.526$, $p=.003$).

Table 3. Healthy controls' mean time post-peak velocity (as a percentage of the movement segment time; ± SD) as a function of direction, hand, and target size for left-right movements.

Young Controls								
	Rightward Movements				Leftward Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	51.1 (5)	51.3 (4.1)	51.4 (3.9)	51.8 (3.9)	51.7 (4.7)	52.3 (4.4)	52.3 (4.5)	52.6 (4.3)
Left Hand	52.0 (4.3)	52.4 (4.5)	51.9 (3.8)	51.8 (4.7)	52.5 (5.3)	52.1 (5.4)	51.8 6.5)	51.5 (5.4)
Elderly Controls								
	Rightward Movements				Leftward Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	48.3 (3)	48.4 (2.6)	48.4 (2.9)	49.3 (3)	50.4 (3.7)	49.8 (3.6)	49.9 (3.9)	50.7 (2.3)
Left Hand	50.8 (3.7)	51.5 (2.7)	51.0 (2.7)	50.8 (3.4)	49.8 (2.1)	48.8 (3.5)	48.4 (3.6)	48.7 (4.2)

Elderly Controls

Peak velocity. Elderly controls showed only a main effect of Target Size ($F(3, 21)=6.98$, $p=.002$) for left-right movements (Table 1), which exhibited significant linear ($F(1, 7)=6.81$, $p=.035$) and quadratic ($F(1, 7)=11.08$, $p=.013$) trends, indicating that peak velocity increased as target size increased but reached an asymptote. For near-far

movements (Table 2), elderly controls showed a main effect of Direction ($F(1, 7)=8.3$, $p=.024$) as well as a Hand x Direction interaction ($F(1, 7)=10.39$, $p=.015$). Post-hoc comparisons revealed that peak velocities of near movements (742 mm/s) were 55 mm/s higher than peak velocities of far movements for the right hand (687 mm/s) ($t(7)=4.60$, $p=.003$) but there was no effect of Direction on peak velocities of the left hand ($t(7)=1.38$, $p=.211$; Figure 11).

Time post-peak velocity. There were no significant main effects or interactions for left-right movements in the elderly control group (Table 3). For near-far movements (Table 4), elderly controls showed only a main effect of Direction ($F(1, 7)=9.83$, $p=.016$) such that near movements had higher time post-peak velocity than far movements (52.1% for near vs. 49.3% for far movements).

Table 4. Healthy controls' mean time post-peak velocity (as a percentage of the movement segment time ; ± SD) as a function of direction, hand, and target size for near-far movements.

Young Controls								
	Near Movements				Far Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	55.3	54.3	54.2	53.8	49.3	50.2	50.6	51.1
	(4.2)	(4.6)	(4.0)	(4.3)	(5.7)	(4.7)	(4.1)	(4.4)
Left Hand	53.7	54.1	53.3	53.7	50.7	50.8	50.9	50.6
	(3.9)	(5.4)	(4.7)	(3.7)	(5.1)	(5.1)	(5.9)	(5.1)
Elderly Controls								
	Near Movements				Far Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	52.2	52.3	52.0	52.6	49.2	49.0	48.6	48.9
	(1.2)	(1.5)	(1.4)	(1.8)	(3.4)	(2.8)	(2.4)	(2.7)
Left Hand	52.5	51.6	51.5	51.7	49.7	50.2	49.3	49.6
	(2.1)	(2.4)	(3.3)	(2.9)	(3.4)	(3.6)	(3.2)	(2.9)

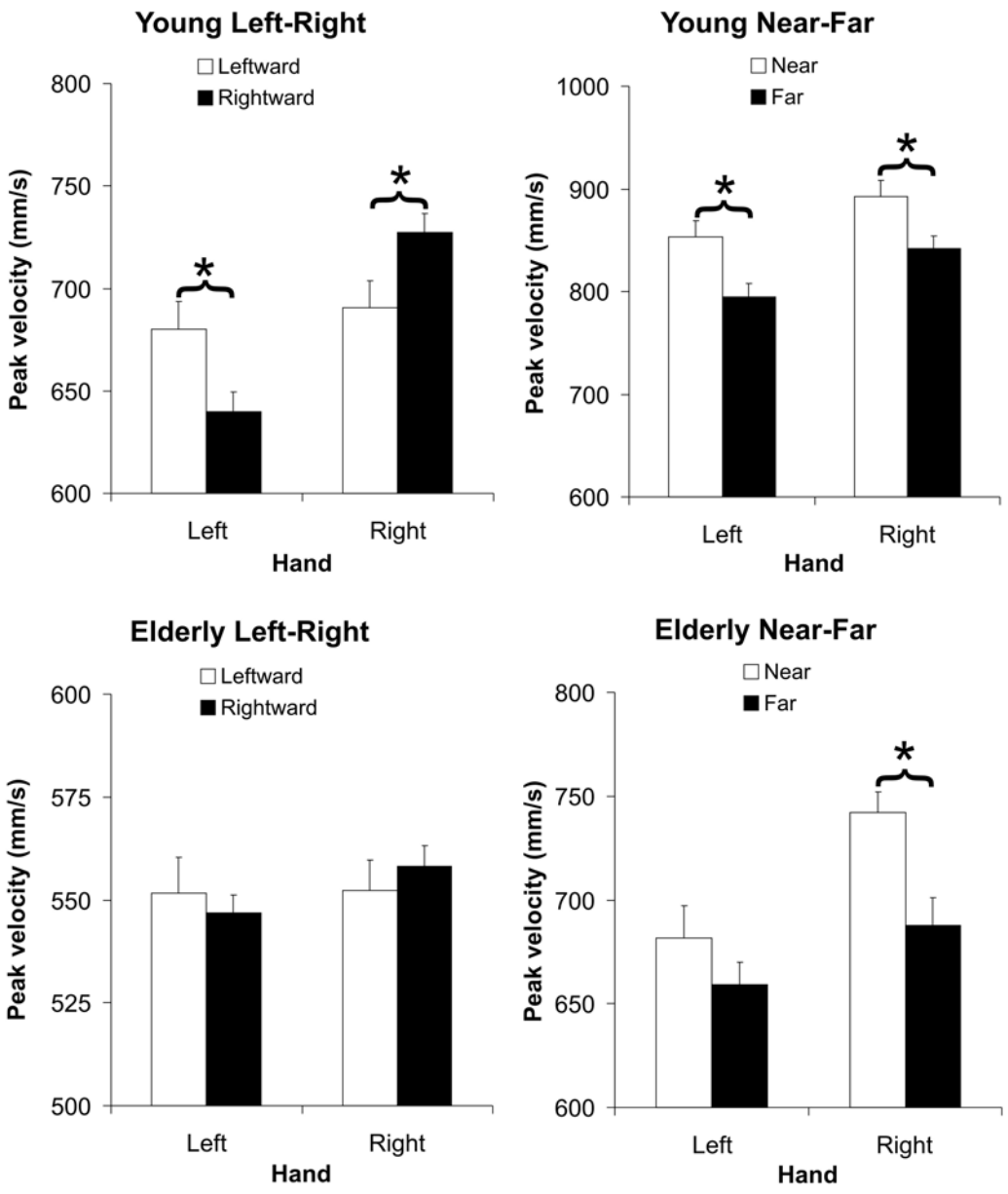

Figure 11. Peak velocity by hand and direction for each control group and axis. * indicates significance at the p=.05 level. Error bars represent within-participant standard error.

ME

Peak velocity. For ME's left-right movements (Table 5), a repeated measures ANOVA revealed significant effects of Hand ($F(1, 19)=24.50$, $p<.001$) and Direction ($F(1, 19)=10.28$, $p=.005$) on peak velocity, as well as a Hand x Direction interaction

(F(1,19)=28.90, p<.001; Figure 12). The difference between peak velocities for rightward movements (471 mm/s) and leftward movements (455 mm/s) with the right hand approached significance (F(1, 19)=4.10, p=.057). For the left hand, peak velocities for leftward movements (525 mm/s) were higher than peak velocities for rightward movements (474 mm/s) (F(1, 19)=35.10, p<.001).

Analysis of ME's near-far movements (Table 6) revealed only a main effect of Direction (F(1, 18)=32.49, p<.001) with near movements having higher peak velocities than far movements (610 mm/s vs. 514 mm/s for near versus far movements respectively; Figure 12).

Time post-peak velocity. A repeated measures ANOVA revealed that for left-right movements (Table 7), ME showed a significant effect of Hand (F(1,19)=24.05, p<.001) qualified by an interaction of Hand and Direction (F(1, 19)=33.83, p<.001). Separate ANOVAs for each hand revealed that Direction was significant for both the right (F(1, 19)=11.60, p=.003) and left hands (F(1, 19)=14.39, p=.001). Overall, time post-peak velocity was higher for the left hand than for the right hand (.564 vs. .525 for left versus right hands respectively). There was, however, a crossover interaction. Time post-peak velocity was larger for the right hand when moving leftward (.544) than when moving rightward (.505). The left hand showed the opposite pattern: time post-peak velocity was larger when moving rightward (.591) than when moving leftward (.538; Figure 13). This is probably due to the biomechanical differences between movements in an ipsilateral direction and movements in a contralateral direction (Carey, Hargreaves, & Goodale, 1996). A similar pattern was found in the control data from the elderly group although it did not reach significance (Figure 13). For near-far movements (Table 8), ME showed a

main effect of Hand ($F(1, 18)=22.39$, $p<.001$) such that time post-peak velocity for the left hand (.600) was higher than those for the right hand (.556) with no other main effects or interactions significant.

Table 5. Mean peak velocities (mm/s) as a function of direction, hand, and target size for left-right movements of patients.

Patient ME

	Rightward Movements				Leftward Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	453	478	481	473	436	472	463	449
Left Hand	472	474	478	472	527	525	523	526

Patient LH

	Rightward Movements				Leftward Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	463	465	452	438	431	440	430	420
Left Hand	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 6. Mean peak velocities (mm/s) as a function of direction, hand, and target size for near-far movements of patients.

Patient ME

	Near Movements				Far Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	629	611	614	615	521	507	523	504
Left Hand	586	606	609	612	515	517	517	509

Patient LH

	Near Movements				Far Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	544	541	552	566	565	556	562	541
Left Hand	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

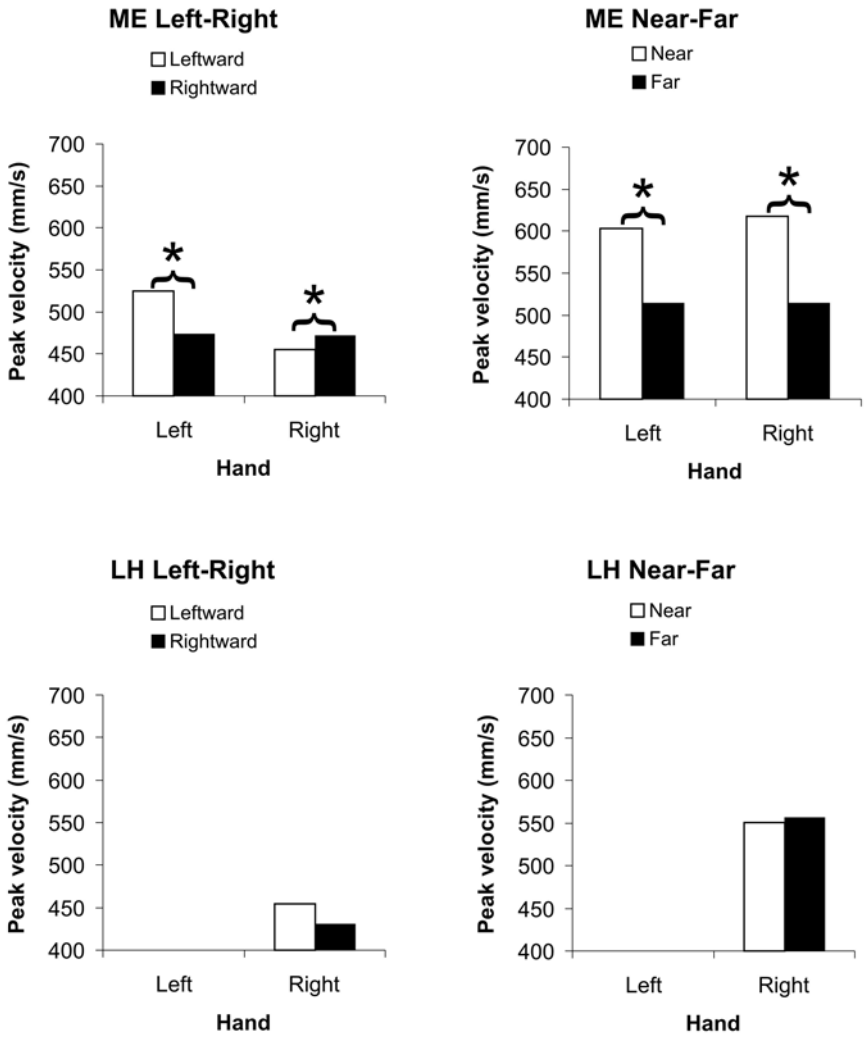

Figure 12. Peak velocity by hand and direction for patients ME and LH for each axis of movement. Because LH did not have full use of his left hand, there is no data for that condition. * indicates significance at the p=.05 level.

LH

Peak velocity. No main effects or interactions were found in LH's peak velocities for either left-right (Table 5) or near-far (Table 6) movements.

Time post-peak velocity. For left-right movements, LH showed a significant main effect of Direction ($F(1, 18)=16.35$, $p=.001$; Table 7). Leftward movements had larger time post-peak velocity than rightward movements (.584 vs. .537). For near-far movements, LH showed a significant Target Size x Direction interaction ($F(3, 51)=2.95$, $p=.041$) with no main effects (Figure 13; Table 8). Separate ANOVAs for each direction, however, did not reveal an effect of Target Size for either. Pairwise comparisons of near and far time post-peak velocity at each Target Size did not find any differences that remained significant after a Bonferroni correction for multiple comparisons.

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Table 7. Patients' mean time post-peak velocity (as a percentage of the movement segment time) as a function of direction, hand, and target size for left-right movements.

Patient ME								
	Rightward Movements				Leftward Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	51.0	50.3	50.0	50.8	54.5	55.3	53.3	54.6
Left Hand	56.1	59.8	58.4	62.0	51.6	56.4	53.9	53.3
Patient LH								
	Rightward Movements				Leftward Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	52.9	51.9	53.1	56.9	59.2	54.9	58.3	57.2
Left Hand	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 8. Patients' mean time post-peak velocity (as a percentage of the movement segment time) as a function of direction, hand, and target size for near-far movements.

Patient ME								
	Near Movements				Far Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	52.0	56.0	53.3	56.5	55.1	58.0	58.0	56.1
Left Hand	59.6	59.1	61.5	60.6	60.1	60.0	59.6	61.2
Patient LH								
	Near Movements				Far Movements			
Target Size (cm)	2	3	4	5	2	3	4	5
Right Hand	59.2	54.9	58.3	57.2	55.9	58.3	57.8	58.4
Left Hand	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Time post-peak velocity: patients vs. elderly controls.

Due to the patients' ages, their most appropriate comparison group is the elderly controls. In order to compare the time post-peak velocity of each patient to the elderly controls, 95% confidence intervals were calculated for the elderly controls. LH's time post-peak velocity was outside the 95% CI for elderly controls in every direction of movement. ME's time post-peak velocity was outside the 95% CI for all combinations of hand and direction except for rightward movements of the right hand (ME's time post-peak = 50.54%; upper bound of the 95% CI for elderly controls = 50.56%).

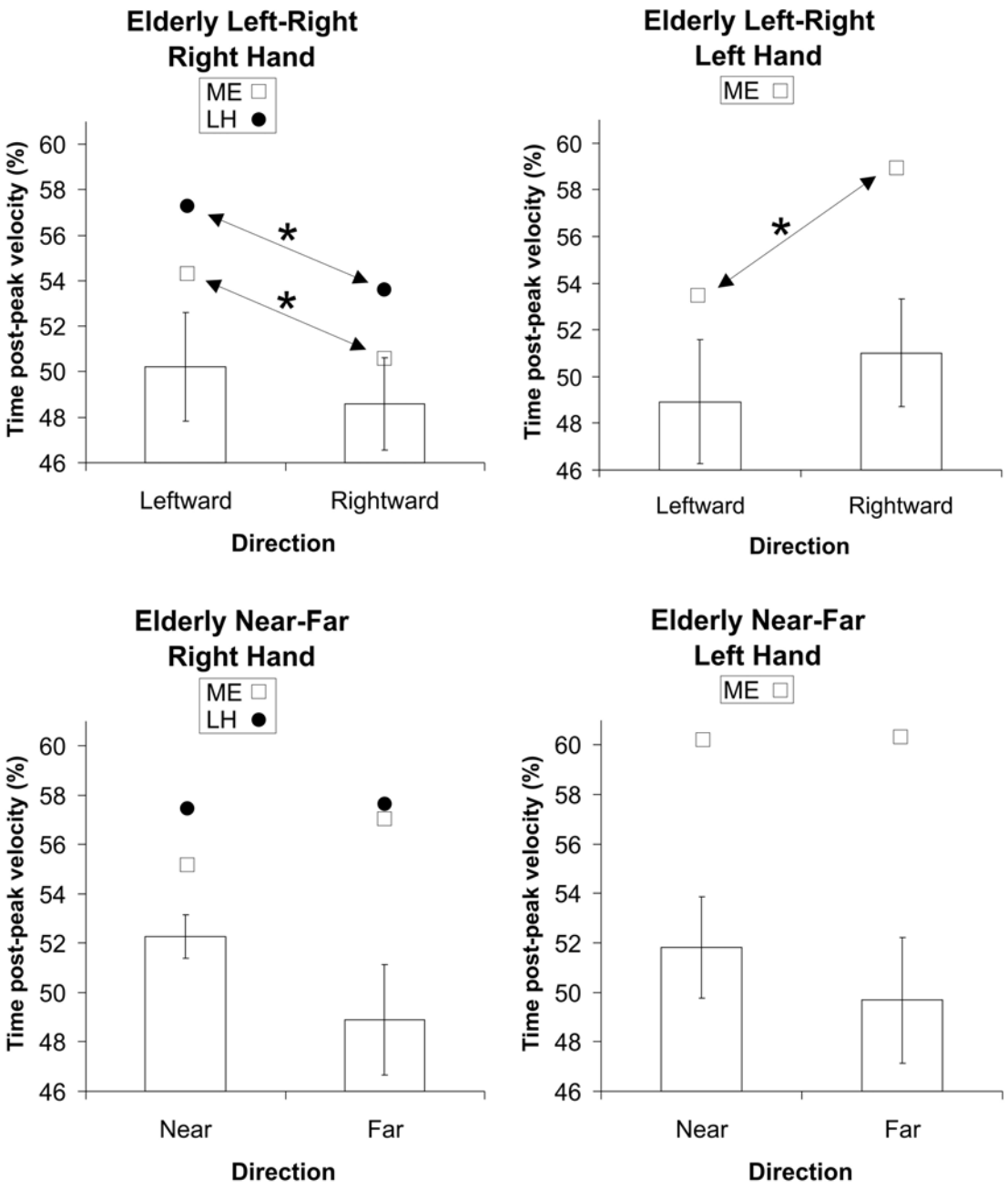

Figure 13. Time post-peak velocity (as a percentage of the movement segment time) by Hand and Direction for the elderly control group and both patients. * indicates significance at the p=.05 level. Error bars represent 95% confidence intervals.

Dwell Time

When inspecting velocity traces for patient ME, it was noticed that her minima were flatter than all other participants (Figure 14). It appeared that her movement velocity dropped below the cut-off for the end of a movement and stayed below this point for some time before she began the next part of the movement sequence. This was seen occasionally in some elderly control participants but was far more prominent in ME's data. For all participants, then, when there was no clear minimum, the previous movement was considered to have ended when the velocity initially dropped below 50 mm/sec for 5 consecutive frames and the next movement was considered to have started when the velocity began to rise again and continued rising for 20 consecutive frames. The time in between was tracked and is referred to here as "dwell time". This is similar to the "down time" defined by Mattingley et al. (1992) but in that case included the time required to react to a stimulus and then continue the movement sequence; in the present study, the participants did not have to wait for a new stimulus to appear and so dwell time is not expected to include any reaction time. This dwell time was included in speed-accuracy trade-off analyses where measures were collapsed over movement direction (and thus reflected the whole movement sequence) but it was not included in the previous analyses that used direction as a factor.

Because only ME displayed this behaviour, it was not possible to compare her performance to that of LH or the healthy controls. As well, the design of the study resulted in differing numbers of target touches on the centre versus the left, right, near, and far targets, which made collapsing for a repeated measures ANOVA difficult.

Accordingly, a simple visual inspection of the data was performed to look for trends that might inform future research. Several interesting patterns of behaviour were noted.

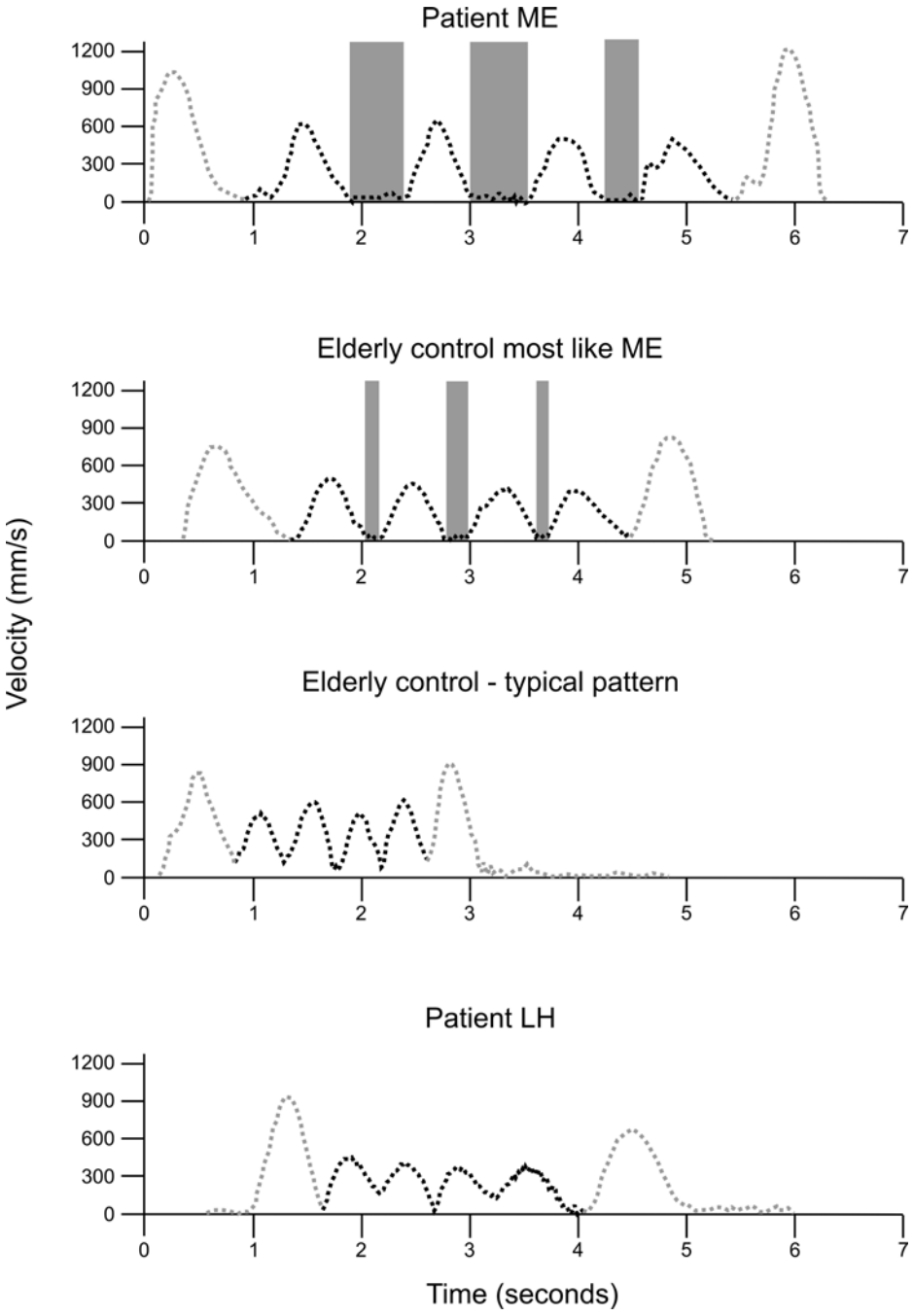

Figure 14. Sample velocity traces from patients and elderly controls showing "dwell time" shaded in grey. The first and last peaks are also indicated in grey as these movement segments were not included in any of the analyses.

It can be seen from ME's dwell time for each target location (Figure 15) that the means for the right hand were roughly equivalent. There is a suggestion of a pattern for the left hand with dwell time lower when touching the far target than the near or centre targets. Figure 16 shows the centre target dwell time for each direction of movement. For left-right movements, the most dwell time occurred when ME was on the centre target moving leftward with her left, ataxic hand. The dwell time for the centre target was strikingly different for near and far movements in both magnitude and frequency: 98% of target touches demonstrated dwell time when ME was bringing her hand back toward her body compared with only 10% when she was reaching away from her body.

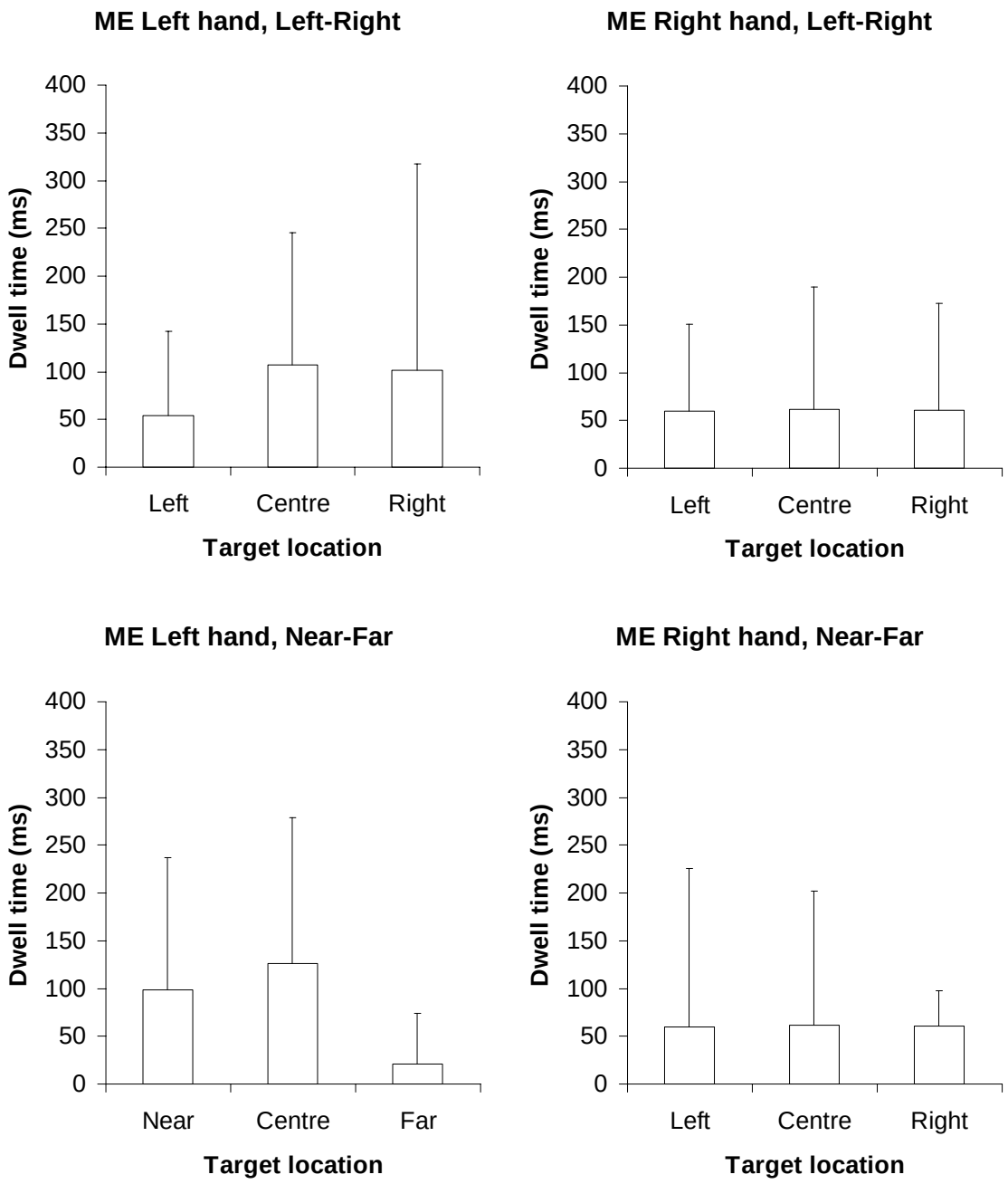

Figure 15. Mean dwell time by target location. Error bars indicate standard deviations.

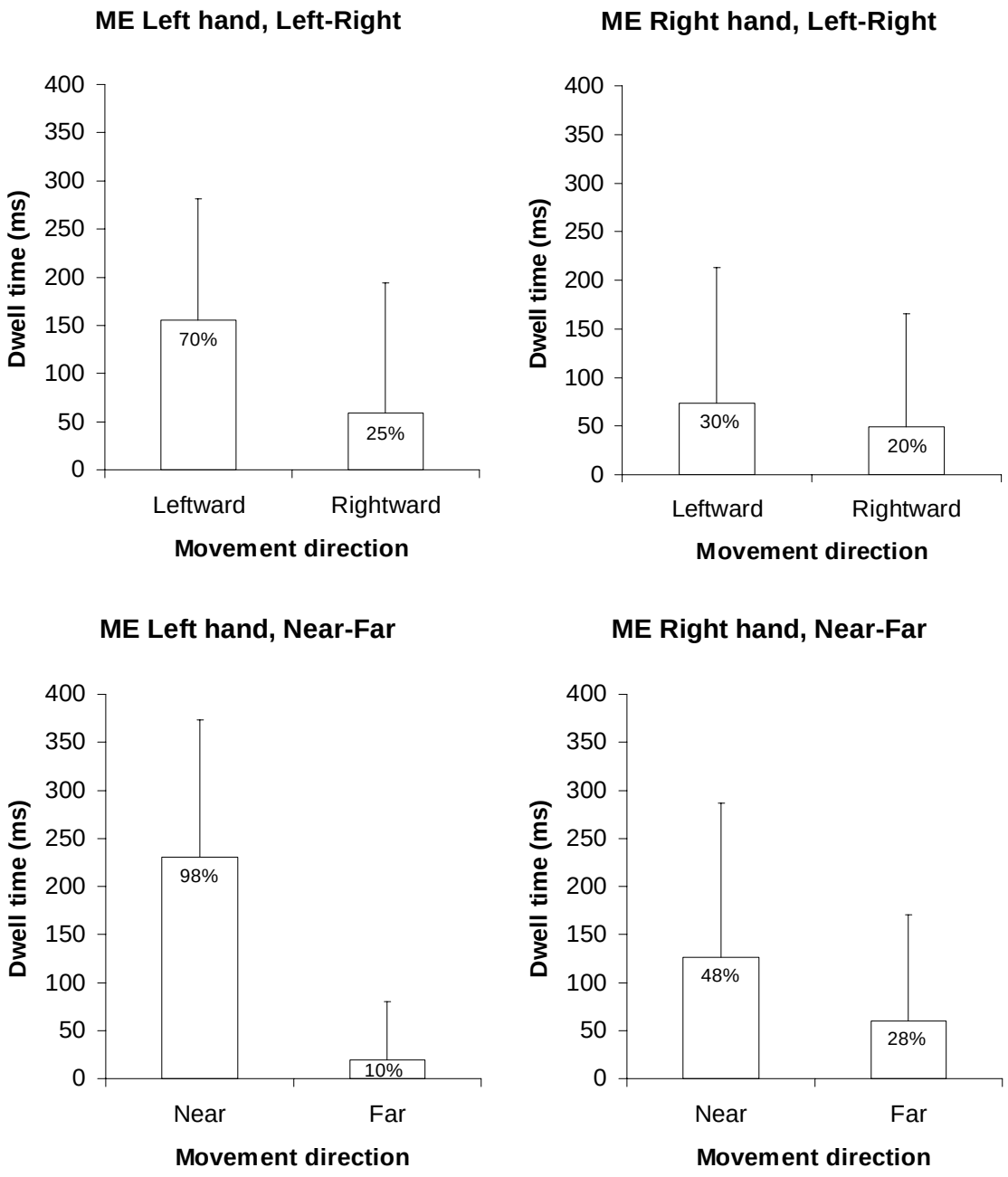

Figure 16. Mean dwell time for centre targets only by direction of movement. Percentage of target touches with non-zero dwell time are indicated on the bars. Error bars indicate standard deviations.

Discussion

Speed-accuracy trade-off analyses indicated that for both control groups, there was a linear relationship between target size and movement time for movements made in both the left-right and near-far directions. In stark contrast to the controls, neither patient showed any relationship between target size and movement time. Similar results were found when peak velocity was examined, with both control groups demonstrating a speed-accuracy trade-off such that, in general, as target size increased, so did peak velocity[2]. The only exception to this pattern was for near-far movements made with the left hand in the elderly control group. Once again, neither patient exhibited the expected relationship between target size and peak velocity. Given that both patients made movements that were slower in total duration and had lower peak velocities than controls (Figures 7-10) it is possible that the absence of a speed-accuracy trade-off in the patients was due to the adoption of a more conservative strategy. That is, the patients may have emphasised accuracy over speed to such a degree that no modulation of performance according to target size was observed. Differences in the *pattern* of performance for near-far movements in ME and large increases in the time spent post-peak velocity for all movements in both patients (discussed in detail below), point to a different explanation. That is, damage to parietal cortex interferes with the normal mechanisms that lead to a speed-accuracy trade-off in healthy controls. This may come about through disruption to on-line adjustments of visually guided reaching movements (Desmurget et al., 1999; Grea et al., 2002; Pisella et al., 2000; Rossetti et al., 2005), or through the inability to generate or make use of internal motor plans (i.e., disrupted motor imagery; Danckert et

[2] In some conditions the speed-accuracy tradeoff plateaued such that the results were best characterized by the combination of a linear and a quadratic trend indicating that peak velocity increased as target size increased only over the first three target sizes.

al., 2002; Sirigu, Duhamel, Cohen, & Pillon, 1996). Despite the notable absence of a speed-accuracy trade-off in the patients, there were aspects of their visuomotor performance that warrant further discussion.

When first exploring the speed-accuracy trade-off in all participants the data was collapsed across the specific direction of movement, making no distinction between leftward and rightward components of a left-right trial. When subcomponents (e.g., the leftward and rightward segments of a left-right trial) of the overall movements were contrasted, healthy controls demonstrated lower peak velocities for movements made in a contralateral direction (e.g., the right hand moving leftwards or the left hand moving rightwards). More specifically, the younger controls were faster to move their right hand toward right space than toward left space and vice versa (Figure 8). This difference is probably due to the biomechanical constraints of the moving limb (Carey, Hargreaves, & Goodale, 1996). A similar pattern of performance was observed in the elderly control group, although for this group the pattern failed to reach significance (Figure 8). The lack of significance in the elderly controls may be due to a more conservative strategy in that group, which might be reflected in their slower overall movement times and lower peak velocities (although it should be noted again here that the elderly controls did still generate a speed-accuracy trade-off). When the pattern of performance for right hand movements was examined within each individual in the elderly control group, six of eight participants showed the same difference as the younger control group (i.e., lower peak velocities for movements made in a contralateral direction). For the left hand, however, there was no clear pattern, with four of the elderly controls having leftward peak velocities higher than rightward peak velocities. The pattern of peak velocity for left-right

movements (i.e., lower peak velocities for movements made in a contralateral direction) may be strongest for the dominant hand (i.e., the right hand) and diminish with age for the non-dominant hand. This is consistent with previous research showing a decrease in manual asymmetries with increasing age (e.g. Francis & Spirduso, 2000; Kalisch et al., 2006). Interestingly, for left-right movements, ME also demonstrated lower peak velocities for movements made in a contralateral direction. That is, her peak velocities were lower for the right hand moving leftwards and vice versa for left hand movements. This suggests that, although ME did not demonstrate a speed-accuracy trade-off in terms of peak velocity, her movements were subject to some of the same biomechanical constraints as seen in healthy controls. Although on visual inspection it appeared that LH demonstrated lower peak velocities for leftward movements made with the right hand (i.e., the same pattern as controls and ME; Table 5), this difference did not reach significance. The more extensive lesion suffered by LH may have led to a greater degree of variability in movement kinematics. Alternatively, the more inferior lesion suffered by LH may have affected this direction of movement (i.e., left-right) more so than does a superior lesion such as the one suffered by ME. This is consistent with previous work in which inferior parietal lesions have been shown to disrupt movement time (and presumably movement velocity) for leftward movements (Heilman, 1985; Husain et al., 2000; Mattingley et al., 1992).

For near-far movements, both control groups and ME demonstrated a consistent pattern of performance such that peak velocity was highest for movements made back toward the body (i.e., near movements) for either hand. The one exception to this pattern of performance was for left hand movements in the elderly control group that

demonstrated the same pattern as just described but was non-significant (Figure 8). Again, as with the pattern of peak velocities for left-right movements, it may be the case that only the dominant hand maintains these differences in a healthy aging population. Interestingly, patient LH failed to demonstrate the same pattern of peak velocity for near-far movements as seen in all other participants (Tables 2, 6). This suggests that the more inferior parietal lesion led to a more pervasive disruption of movement control (i.e., with all directions of movement similarly affected) than does a superior lesion. Of course, this is a dramatic oversimplification of the comparison being made between these two patients who differ in pathology, behavioural sequelae and lesion locus (not to mention lesion volume). It does seem clear, however, that LH showed fewer similarities to controls in terms of the *pattern* of his kinematic data than did patient ME, which suggests a more pervasive disruption in visuomotor control in this patient.

Perhaps a more informative indicator of the difficulty of ballistic pointing movements is the time spent decelerating prior to contact with the target. The amount of time spent slowing down in a single movement phase can be taken as an index of the difficulty or the degree of accuracy required of the movement being made. The amount of time post-peak velocity was calculated for each movement segment and represented as a percentage of the total movement time for that segment (hereafter referred to as time post-peak velocity). Both control groups demonstrated a consistent amount of time post-peak velocity for leftward and rightward movements of either hand (Figure 13; Table 3). In contrast, for near-far movements made with either hand, more time was spent post-peak velocity for near movements (i.e., toward the body) than for far movements in both control groups (Figure 13; Table 4). The pattern of performance for left-right movements

suggests that both directions of movement were equally difficult for healthy controls. In contrast, the greater portion of time spent post-peak velocity for near movements suggests that acquiring targets when moving toward the body requires more visuomotor guidance than when moving away from the body. This may be a consequence of our everyday experiences with goal-oriented arm movements. For example, when we intend to grasp an object the first movement to be made is always away from the body and can afford to be ballistic in nature (i.e., reaching out to pick up a full cup of coffee). In contrast, when we bring those same objects back toward the body it is generally with the intention of performing more fine-grained motor manipulations of the object, such as is required by tool use (e.g., using a pen or a pair of scissors). Such actions that bring objects back toward the body may therefore require a greater degree of control. For example, when bringing a cup full of hot coffee up to the mouth it is advisable to slow down dramatically before making contact with the lips.

For rightward and leftward movements ME displays a similar pattern to that observed in her peak velocities: more time is spent post-peak velocity for movements made in a contralateral direction (e.g., right hand moving leftward). Patient LH demonstrates a similar pattern of performance to ME for rightward and leftward movements of the right hand (Figure 13). ME's left hand movements showed times post-peak velocity that were well outside the 95% confidence interval of elderly controls (Figure 13). This was also true of leftward movements of the right hand. In other words, for the time spent post-peak velocity ME shows the classic hand and field effects normally observed in patients with optic ataxia (Perenin & Vighetto, 1988). More specifically, movements toward left hemispace are disordered in both hands, while

movements in all directions are impaired for the left, ataxic hand. Only movements of the right hand were available for patient LH with both leftward and rightward directions showing dramatically more time spent post-peak velocity than controls (Figure 13). Although LH's rightward movements were outside the 95% confidence interval of elderly controls, it was also evident that he spent far more time post-peak velocity for leftward movements of his right hand. This pattern is consistent with previous work in patients with inferior parietal lesions showing longer movement times for this direction of movement (Heilman, 1985; Husain et al., 2000; Mattingley et al., 1992), consistent with LH's velocity pattern.

For near-far movements, the pattern of performance for both patients differed more obviously from the pattern observed in controls. For ME, time post-peak velocity was higher for far than for near movements for her right hand. Although this difference was not quite significant ($p=.075$), it was in the opposite direction to the pattern observed in controls. ME's times post-peak velocity for near-far movements of the left hand did not differ. LH showed no difference in time post-peak velocity for near-far movements of his right hand. It is important to note here that in all conditions (with one exception noted below) the time post-peak was outside the 95% confidence interval of the elderly controls for both patients (Figure 13). Patient ME provided the one exception to this in that rightward movements of the right hand were just inside the upper bound of the 95% CI for controls (ME's time post-peak = 50.54%; upper bound of the 95% CI for controls =50.56%). In addition, both patients demonstrated a greater degree of impairment in their near-far movements than they did in their left-right movements. While most research

exploring visuomotor control in stroke patients has focused on lateralised deficits[3], this last result suggests that movements that bring objects back toward the body, perhaps for the purpose of more detailed manipulation, may well be more impaired following right parietal damage than are lateralised movements.

In summary, for patients ME and LH movements in both the left-right and near-far directions demonstrated obvious differences in absolute terms (e.g., longer movement times, lower peak velocities and a greater portion of the movement spent post-peak velocity), as well as showing some dramatic differences in their pattern of performance when contrasted with controls. The most notable differences in the pattern of performance (as well as in absolute terms) were observed for the time spent post-peak velocity in near and far movements (Figure 13). For leftward and rightward movements patients and controls spent more time post-peak velocity for movements made in a contralateral direction (although this was only significant for the patients). Interestingly, for near-far movements, in which controls demonstrated a significant difference such that near movements had longer times post-peak velocity, neither patient demonstrated such a pattern. To reiterate, this suggests that movements in the sagittal plane (toward and away from the body, centred on the trunk), both patients demonstrated a greater degree of impairment when contrasted with left-right movements.

While there are substantial differences in the symptom profile and lesion characteristics of the two patients (Methods; Figures 3 and 4) it is worth considering the differences in performance that may relate to differential involvement of the inferior and

[3] While this is not strictly true for research examining apraxia, which typically arises as a consequence of *left* parietal injury and in which gestural control and sequences of movements are affected independent of the region of space in which they are performed, it is certainly true of research exploring visuomotor deficits following right hemisphere lesions.

superior parietal cortices. For patient LH, in which the superior parietal cortex was spared, movements in all directions were impaired relative to controls. Most notably, in terms of time post-peak velocity, LH was well outside the 95% confidence interval of the elderly controls for all directions of movement (Figure 13). The largest deficit was evident in the time spent post-peak velocity for leftward movements made with the right hand (Figure 13; note that LH was unable to use his left hand at the time of testing). This is consistent with previous work demonstrating poor control of leftward movements in patients with neglect arising from inferior parietal lesions. Given that LH was no longer demonstrating neglect at the time of testing, this result implies that a movement deficit of this kind is not critical to the demonstration of neglect symptoms.

Two possibilities exist for the range of impairments observed in LH. First, it may be the case that on-line control of movements, which is heavily dependent on visual feedback, is disrupted. Alternatively, the initial planning of movements may be impaired. Although these two possibilities were not directly tested in the current study (no emphasis was placed on the speed of the first movement in a sequence, making any reaction time analysis – necessary for testing assumptions about movement planning – irrelevant), there is indirect evidence from other studies that inferior parietal damage does lead to greater deficits of movement planning rather than execution. Husain and colleagues (2000) found that neglect patients with right parietal damage demonstrated larger reaction times for movements to be executed toward leftward targets but showed no difference in movement time when moving leftward or rightward. This strongly suggests that movement planning but not movement execution was impaired in these patients. Danckert and colleagues (2002) have shown that in one patient with an inferior

parietal lesion the expected speed-accuracy trade-off for imagined movements was severely impaired, suggesting that internal motor programs (i.e., efference copies of intended actions) are disrupted by inferior parietal damage. Other converging evidence to suggest that the planning of movements depends more on the integrity of the inferior parietal cortex comes from research exploring the consequences of superior parietal lesions. First, a series of studies by Pisella and colleagues (Gréa et al., 2002; Pisella et al., 2000; Rossetti et al., 2005) have shown that on-line corrections of pointing movements in the face of perturbations of target position depend heavily on the superior parietal cortex. The strongest support for this comes from a somewhat counterintuitive finding in a patient with optic ataxia arising from bilateral parietal lesions - patient IG. In this study (Pisella et al., 2000) participants were asked to stop pointing to a target if it changed position in flight. Healthy individuals failed to do this – that is, they automatically corrected their movement to account for the new target position – on around 15% of trials. In contrast, IG had no trouble arresting her movements in response to changes in target position (i.e., she demonstrated very few automatic corrections) such that she followed the experimental directions more efficiently than controls. In short then, the errors of controls (adjusting movements to account for target perturbations despite instructions to the contrary) represent the normal function of what Pisella and colleagues called the "automatic pilot" – an automatic on-line movement correction system damaged in IG. In other work with patient IG, her primary deficit – impaired reaching for peripheral targets – is dramatically improved when a delay is imposed between target presentation and a go signal to initiate a movement (Milner et al., 2001, 2003; Rosetti et al., 2005). This implies that when a patient with superior parietal damage is given more

time to plan a movement, which presumably relies on the function of undamaged regions of inferior parietal cortex, her performance improves dramatically.

Finally, Coello and colleagues (2007) demonstrated in the same patient tested extensively by Pisella and colleagues (patient IG), that the almost complete absence of superior parietal cortex does not lead to an increased susceptibility of actions to pictorial illusions. That is, in healthy individuals the ability to reach out and grasp an object embedded within a size-contrast pictorial illusion is determined by the absolute metrics of the target to be grasped and not the perceived target size which itself is heavily influenced by the illusory context (e.g., Aglioti, DeSouza, & Goodale, 1995). The standard explanation of this effect suggests that the visual control of actions is controlled by the dorsal visual pathway which goes from V1 through superior portions of posterior parietal cortex (Goodale & Milner, 1992; Milner & Goodale, 1995; Ungerleider & Mishkin, 1982) and is concerned only with the absolute metrics of target objects as they relate to the effectors used to act upon them. A strict prediction of this model then would suggest that a patient with dorsal stream lesions such as IG should demonstrate a significant influence of illusory contexts on both perceived target size and on her control of actions directed toward those targets. The fact that she performed in a manner identical to controls in several illusory contexts suggests that visuomotor control is immune to illusions by virtue of activity in regions of inferior and not superior parietal cortex. Coello and colleagues suggest that this may be due to the role played by inferior parietal cortex in the planning of movements (see also Danckert et al., 2002).

Taken together, there is converging evidence to suggest that the inferior parietal cortex plays a greater role in movement planning than in movement execution. In this

context, the greater time post-peak velocity for all movement directions (with leftward movements most affected) observed in LH may be more likely to be a consequence of a disruption in his ability to plan movements.

The expected hand and field effects of optic ataxia (Perenin & Vighetto, 1988) can be seen in ME's time post-peak velocity for left-right movements. Although ME demonstrated a mild field effect on clinical testing (i.e., movements of the right hand into left space were slower and more cautious than movements of either hand in right space even to the naked eye), her kinematic profile did not support a strong field effect. That is ME's right hand movements toward left space had higher time post-peak velocity than rightward movements – a pattern similar to the controls, although the difference between leftward and rightward movements was much larger for ME (Figure 13). In contrast, ME shows a strong hand effect seen in higher time post-peak velocity for movements with the left hand (and for either direction of movement) than with the right hand (Figure 12). These effects were evident in time post-peak velocity but not in peak velocity, possibly because the task was performed entirely in central vision and the effects of optic ataxia are most clearly evident when performing reaching movements to targets in peripheral vision (Perenin & Vighetto, 1988). Overall, ME's left-right movements are impaired when compared to controls but show the same directional patterns in both peak velocity and time post-peak velocity (Figures 11, 12, 13).

The peak velocity of ME's near-far movements, while being much lower than those of controls, demonstrated a similar pattern (Figures 11, 12). In contrast, ME's time post-peak velocity for near-far movements were not only well outside the 95% confidence interval of elderly controls but also failed to demonstrate the strong pattern

that was evident in the healthy older group (Figure 13). In fact, both groups of controls demonstrated more time post-peak velocity for near movements than for far movements of either hand (Figure 13; Table 4). In contrast, ME did not show any effect of direction but did have higher time post-peak velocity for movements made with the left, ataxic hand than with the right hand. Previc (1990, 1998) has argued that the dorsal "how" pathway, of which the superior parietal area damaged in ME is perhaps the most substantial part, is specialised for visuomotor processing in peripersonal space. Although one might have reasonably expected that ME would be more impaired when moving toward peripersonal space (i.e., toward the near target), she did not show the expected increase in time post-peak velocity when reaching toward the body when compared with reaching away from the body (Figure 13). It is important to note here that all the movements in this study occurred *within* peripersonal space, which may have led to a similar degree of impairment for movements in both directions. In addition, ME was able to fixate all targets and might be expected to show a discrepancy between near and far movements only when targets are maintained in peripheral vision. What is clear is that movements made both toward and away from her body in peripersonal space were impaired when compared to elderly controls.

Although ME's time post-peak velocity for near and far movements did not differ, some support for a greater degree of impairment for movements made toward the body can be seen in dwell time data for her left hand (Figure 16). Recall that dwell time was not included when calculating times post-peak velocity. Visual inspection of the data revealed that when touching the centre target on her way to the near target (i.e., moving back toward her body), she rested for a longer time (an effect evident on a higher

percentage of target touches) than when she touched the same centre target on her way to the far target (i.e., moving away from her body). This discrepancy between directions was exacerbated for the left hand (Figure 16). It is not entirely clear what causes ME to spend more time in contact with the target for this particular direction of movement and further research that explicitly addresses this unexpected component of her kinematic profile will obviously be needed to address any hypotheses concerning it. Given the previously discussed suggestion that movement planning is more likely to depend on the integrity of inferior parietal cortex – a region clearly spared in ME (Figure 3) – this component of her visuomotor performance is more likely to reflect in some way the on-line execution of movements. One possibility is that ME has greater difficulty than would be expected in comparing her initial motor plan with the actual outcomes of her movements. Such a process, which depends on efference copies of the intended action, is likely to be continually active in healthy individuals such that movements can be continually updated based on any discrepancies between anticipated outcomes of intended actions and the actual perceptual motor outcomes (see Davidson & Wolpert, 2005, for a review). In other words, the dwell time observed for movements made back toward her body may represent a "catch-up" phase in which ME can now compare intended motor plans with actual outcomes. It is interesting then to note that this additional time needed to compare intended actions with actual outcomes – a process that is likely the key component of *on-line* control of movements – is greatest for movements made back toward the body. This not only provides some support for the notion that the superior parietal cortex maintains a stronger representation for peripersonal space (Danckert & Goodale, 2001; Previc, 1998), but also suggests that this is contingent upon

the kinds of actions to be performed in this region of space. That is, all pointing movements tested here were performed in peripersonal space. For ME it is those movements back toward the body that were most impaired.

Finally, several key aspects of ME's performance warrant consideration in the context of current models of optic ataxia. While most models of optic ataxia have emphasised the fact that visuomotor performance is worst for movements made in peripheral vision, the data here suggest that central vision is far from spared (see also Grea et al., 2002, Pisella et al., 2000). The key element to visuomotor deficits in optic ataxia that are evident even when the patient is allowed to fixate the targets of visually guided actions is the need for on-line control. The dwell time observed for ME's movements (notably absent in the patient with a more inferior parietal lesion, LH) is probably related to some kind of deficit in on-line control. Perhaps more importantly, the direction in which ME is most impaired is for movements in the sagittal plane (i.e., toward and away from the body). One fundamental component of most theories of optic ataxia is the so-called "field effect" (Perenin & Vighetto, 1988). That is, patients demonstrate pointing errors that are largest for targets in contralesional space. The data shown here does not necessarily dispute this component of optic ataxia *for movements made in peripheral vision*. However, when allowed to fixate targets ME was slower for near-far movements and demonstrated the largest portion of dwell time for this direction when compared with left-right movements. In addition, the proportion of trials in which ME spent some dwell time on the central target was highest for movements made back toward the body with either hand (98% and 48% of trials for the left and right hands respectively; Figure 16). Taken together, this suggests that ME has a deficit in

visuomotor control for movements back toward the body. The kinds of movements being invoked here are those that require fine-grained manipulation of objects in peripersonal or personal space (e.g., using scissors or buttoning a shirt for peripersonal and personal space manipulations respectively). This may suggest a hitherto ignored component of optic ataxia – a deficit in object manipulation in peripersonal and personal space. Obviously, further research is needed to explore the veracity of this hypothesis.

The results of the current study demonstrate differential effects of inferior and superior parietal lesions on the control of visually guided pointing movements. Following inferior lesions (patient LH) the control of the ipsilesional hand demonstrates pervasive deficits for all directions of movement. Although not directly examined here, the pervasive nature of these deficits, together with a wealth of other research, suggests that the inferior region of right parietal cortex plays a critical role in the planning of visually guided movements throughout peripersonal space. In contrast, more superior lesions (patient ME) appeared to impair movements in the sagittal plane more so than movements made in the fronto-parallel plane. In addition, movements made toward the body appeared to show a greater degree of deficit than did movements made toward the left or right visual space. Taken together, these results suggest that the realm of movement control most affected by superior parietal lesions is for movements made back toward the body in peripersonal space.

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