

## Pointing to two imaginary targets at the same time: Bimanual allocentric and egocentric localization in visual form agnostic D.F.

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### ABSTRACT

We have previously shown the visual form agnostic patient D.F. has spared sensorimotor utilization of visual information relative to her poor perceptual processing of the same stimulus attributes. Her visuo-motor skills are, however, only normal when egocentric visual coding can be used in the task. In other words, her egocentric sensorimotor processing is intact while her 'allocentric' coding of spatial position is impaired. The current investigation extends these previous observations by comparing D.F.'s performance in bimanual pointing to pairs of stimuli directly (the egocentric task) versus pointing to the homologous positions on an adjacent workspace (pantomimed reaching, the allocentric task). The results showed greatly superior pointing accuracy in direct pointing compared to pantomimed pointing. The mechanisms supporting her limited but remaining sensitivity to spatial relationships during pantomimed pointing remain unknown. These residual skills may reflect partially spared categorical coding and/or internal sensorimotor self-cueing.

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### 1. Introduction

The "two visual systems" model advanced by Milner, Goodale and their various colleagues suggests that dorsal stream functions should be characterized in terms of sensorimotor exploitation of sensory attributes (Milner & Goodale, 1995). These attributes are not restricted to spatial features of a target for localization; they include object-based properties such as size and orientation, important for controlled grasping. Other models, particularly that of Ungerleider and Mishkin (1982), suggests that the occipito-parietal regions of the dorsal stream are important for the processing of spatial attributes of stimuli (for purposes of spatial perception as well as the spatial guidance of actions).

Many studies by us and our colleagues have shown a strong dissociation between using sensory information for perception and action in the visual form agnostic patient D.F. There is little disagreement that D.F.'s sensorimotor responsiveness to size, orientation and distance is clearly far better than her perceptual sensitivity to those same visual characteristics. Nevertheless, in some limited contexts her sensitivity to some visuospatial attributes is better than chance, even if the response does not require directed movement to the source of the information (e.g. Carey, Dijkerman, &

Milner, 1998; Murphy, Carey, & Goodale, 1998). For example, her distance estimates are appropriately scaled to the physical distance of a stimulus, although she consistently underestimates by as much as 40–50% (Carey et al., 1998; Mon-Williams, Tresilian, McIntosh, & Milner, 2001). These results have led to interesting debates about how spatial functions can be fractionated. In the case of our visual agnostic patient D.F., the allocentric versus egocentric distinction fits quite well with several experimental outcomes. Allocentric spatial attributes relate distinct objects to one another, while egocentric spatial attributes relate a single target attribute to a reference point somewhere on the observer.<sup>1</sup>

In a recent paper (Carey, Dijkerman, Murphy, Goodale, & Milner, 2006) we expanded on earlier work (Murphy et al., 1998) on the limits of D.F.'s ability to make allocentric spatial judgements. In the later experiments, we showed that requiring a sensorimotor response is not in itself sufficient to allow for near-normal localization in pointing. D.F. made aiming movements directly to coloured tokens ("tiddlywinks") on a fixed workspace containing 3–5 elements. Her accuracy at doing so was excellent, and even extended to multiple movement sequences. In a pantomime-like variation, we required a spatial displacement of the response to a homol-

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<sup>1</sup> Early arguments suggested shoulder centered coordinate schemes for pointing (Soechting, Tillery, & Flanders, 1990), whereas more recent accounts suggest that hand movements might be encoded in parieto-frontal circuits in eye-centered representations (see Crawford, Medendorp, & Marotta, 2004 for review).

ogous workspace (that is, pointing to the place on a blank array corresponding to the location of the specified target in the stimulus array). This variant caused D.F. considerable impairment, in spite of unlimited viewing time of the stimulus array, which was easily within sight of the displaced workspace.

In the current investigation, we extended these earlier observations with an additional study. Although D.F.'s aiming abilities with one hand have been characterized previously (Carey et al., 1998; Milner, Dijkerman, & Carey, 1999), little is known about her capacity to move to two different targets simultaneously. D.F.'s good sensorimotor skills may depend on eye–hand coordination patterns restricted to single targets which she foveates as part of a naturally unfolding sensorimotor act. Some bimanual tasks in neurologically intact participants seem to require sequential foveations that can precede the hand's approach to the target by considerable lengths of time (e.g. Flanagan, Merritt, & Johansson, 2009). Little is actually known about eye movements or attentional biases to laterally displaced targets to be pointed at simultaneously with both hands (although see Riek, Tresilian, Mon-Williams, Coppard, and Carson (2003) who suggest a serial saccadic strategy in a stylus aiming task).

Even if D.F. could succeed at a bimanual direct pointing task, we suspected that bimanual pantomimed pointing would represent a substantial challenge to her. Good performance in the bimanual pantomime variant would require D.F. either to encode the two stimulus positions as a vector and then translate that vector onto the response array, or to encode each stimulus position separately on the stimulus array and transpose those visuomotor codes to the blank response array after orienting her body towards it. The former strategy requires coding the “visuospatial gestalt” formed by any stimulus pair and translating it into a bimanual motor program; the latter strategy would utilize independent coding of each stimulus location and transforming each into a single, separate unimanual motor program. Given her relatively laborious spatial judgements about inter-stimulus distance (Carey et al., 2006; Murphy et al., 1998) with these displays, we reasoned that the translation of a bimanual response in the pantomimed condition would represent a particular challenge to her limited visuospatial skills. The second strategy, like that used in unimanual pointing, seemed likely to tax her known abilities to use sensorimotor coding to accomplish certain ostensibly perceptual tasks through self-cueing (Dijkerman & Milner, 1997; Murphy, Racicot, & Goodale, 1996) because she would need to use this approach to generate two responses rather than just one. D.F.'s performance on this new task was examined after testing movements to single targets and multiple target sequences (as reported in Carey et al., 2006). For this study, we required her to point to two specified targets at the same time, using her left for one target and her right hand for the other.

## 2. Method

### 2.1. Participants

D.F. is a right-handed woman who suffered brain damage after accidental carbon monoxide poisoning 10 years prior to testing (at which time she was 43 years old). Her lesions are diffuse but are their most dense in occipito-temporal regions of the ventral stream, including area LO (Carey, Harvey, & Milner, 1996; Goodale & Milner, 2004; James, Culham, Humphrey, Milner, & Goodale, 2003; Milner et al., 1991). D.F.'s shape, orientation and face processing perception had continued to be very poor at time of testing. Her ability to perform spatial judgments is also impaired (Carey et al., 1998, 2006; Milner et al., 1999; Murphy et al., 1998), although not as dramatically as her judgments about the object-based properties such as orientation and shape. In contrast, her colour vision is relatively spared (Milner & Heywood, 1989), which allowed for identification of specific target pairs required for this study.

Two control subjects matched for sex, handedness, and approximate age, with no history of visual, neurological, or psychiatric disturbance were also tested (C.L., aged 42, and C.H., aged 36).

### 2.2. Stimuli

Like Murphy et al. (1998) and Carey et al. (2006) we used coloured tokens (Tidlywinks) as stimuli because they could be reliably discriminated from one another by D.F., despite her perceptual troubles with other types of object identifier such as shape. Nine 21 cm × 21 cm arrays (three each of three, four or five tokens) were used for blocks of direct and pantomimed pointing trials. Two of the arrays were linear, although D.F. did not seem to benefit from this fact in her spatial copies of the target arrays (described in Carey et al., 2006). For the bimanual movements required in this study, inter-target distances varied from 33 to 200 mm; inter-target slopes varied from 12° to 88°.

### 2.3. Procedure

#### 2.3.1. Direct and pantomimed pointing

A blank 21 cm × 21 cm response sheet was presented to the right of the stimulus array, separated by 4 cm. The participants were required to make pointing movements with both hands (without terminal adjustment after landing) to specified target pairs. In ‘direct’ trials, they pointed directly to both specified tokens on the target array. In ‘pantomime’ trials, participants were asked to point to the two locations on the blank sheet that were identical to the locations of targets on the adjacent stimulus array (“as if the array of tokens were placed on top of the blank sheet”). Judgements of number of tokens, the pair closest to one another, and the pair most distant from one another were made for each stimulus array before any pointing responses were called for. Pantomimed single movements defined by the 3, 4 or 5 token locations, as well as double, triple, and (for the four and five place arrays) quadruple and pentuple-step movements were all performed before the bimanual movements (see Carey et al., 2006). As a consequence, all of the participants had considerable exposure with all of the tokens on each array before the bimanual movements were required. However, pantomimed trials were carried out before any physical contact with the actual target arrays.

For the bimanual trials reported here, the experimenter named the pair orally at least two times and asked the participant to repeat the target colours aloud twice, while attending to the individual item locations on the target array. The experimenter then said “three, two, one, go!” and manually initiated data collection before the go signal. The same 58 target pairs were used in pantomime and direct target trials.

D.F. and controls were given several practice trials with the first two arrays before data collection commenced. Hand movements directly towards the stimulus array were not allowed until the direct pointing trials commenced; but eye and head movements between arrays were unrestricted and encouraged.

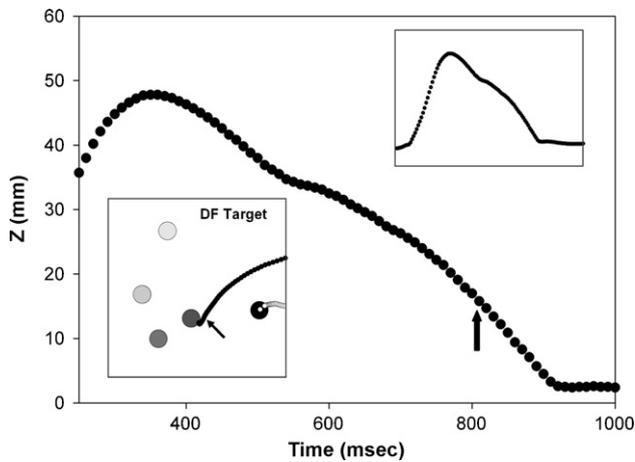
D.F. was tested in three separate sessions within a 5-day period. Control participants C.L. and C.H. were tested in two sessions within a 3-day period. Sessions were video and audio-recorded from an overhead videocamera. Participants wore a lightweight infra-red emitting diode (IRED) placed on the nail of the index finger of their right and left hands. Movement paths were recorded at 100 Hz using an *Optotrak* 3020 system (Northern Digital Inc., Waterloo, Canada). After each session, arrays were replaced on table-marked reference points, and token centre coordinates were recorded. Pantomime response calibrations were achieved by placing the stimulus array in the identical position previously occupied by the blank pantomime array. Movement onset was defined as a 10 frame increase in resultant velocity from a local minimum, where the first of these frames exceeded 10 mm/s. Movement paths were plotted using *Sigmaplot* software (Systat Software, Inc.) and were colour-coded to match the appropriate target required for the sub-movement.

We chose to estimate *terminal* error rather than *endpoint* error as in the target-directed trials, because there was a slim possibility that tactile feedback from the token edges might drive subtle error corrections at the end of movement which might not be visible to the naked eye of the experimenter or to the overhead video-recording. Therefore we used X and Y coordinates from each finger at a point 50 ms before dropping below the 1 cm level in the Z-axis (“up-down” relative to the table surface). After calibration (where the markers of the cube sit slightly above the table surface), the workspace was such that the participants finger markers were at a Z coordinate of slightly less than zero as they rested on the table in their start positions. Effectively this procedure examines accuracy before any contact with the tokens in direct trials was possible (see Fig. 1 for an example).

Unfortunately, technical problems with one of the markers and positioning of the workspace relative to the Optotrak resulted in missing markers from one hand or the other in many of D.F.'s trials (although all trials were clearly visible on the videotape from the overhead camera and D.F.'s performance was consistent throughout the bimanual experiment). Nevertheless, for D.F. 59 target movements and 62 pantomimed movements contained accurate data for the terminal phase of both movements for the calculation of terminal error as discussed above. We used the identical trials in the control participants, unless they were missing data and then a substitution was made from another pair of targets or pantomimes. We were also able to use these trials to examine the synchrony of the landing phase across the two hands.

## 3. Results

As we have reported previously, D.F. performed as well as controls on judgments of nearest and furthest pairs (13/18 versus C.L.



**Fig. 1.** Movement accuracy was estimated from a point 50 ms before the finger IRED dropped below 10 mm in height. The lower inner panel depicts the X and Y reach paths on this particular trial by D.F. The upper small panel shows the Z profile of the longer movement (in black) as a function of time. The larger figure illustrates the last half of the movement in Z. The arrow indicates the frame whose X and Y coordinates were used for calculating movement accuracy.

15/18, C.H. 14/18), and counted all of the arrays successfully (she did have to self-correct on one trial). Every one of her errors was made to the second closest (or second furthest, as appropriate for the question) pair for the particular array. Nevertheless observations during testing were confirmed by examination of the videotapes, which showed a much more slavish strategy in D.F.: she invariably identified each colour on the array in turn, and then would repeat the sequence aloud before reporting her decision. She also self-corrected on the first array, after a long series of movements and copying the array with her own set of tokens (i.e. after multiple opportunities to enumerate, rather than subitize<sup>2</sup> the arrays).

Fig. 2 illustrates a sample target and pantomime trial from D.F. and the control participants. Mean terminal error for direct and pantomimed bimanual reaches appear in Fig. 3, collapsing across hands as the error patterns were quite similar.<sup>3</sup> D.F.'s terminal errors were compared to those of the controls using Crawford and Howell (1998) modified *t*-test for small control group size (the rationale of advantages of are discussed in Carey et al., 2006; see also Crawford & Garthwaite, 2002). We used one-tailed tests because the null hypothesis was that D.F. would perform more poorly than the two control subjects. In direct pointing, D.F.'s terminal errors were not significantly different than controls ( $t(1)=3.65$ ,  $p > 0.05$ , one or two-tailed). She was significantly worse than controls at pantomimed pointing ( $t(1)=112.6$ ,  $p < 0.0005$ , one-tailed).

We also examined accuracy in direct and pantomimed pointing by calculating the inter-finger distance and orientation at movement termination (Fig. 4), and comparing these with inter-target distance and orientation. These data appear in Fig. 5. Remarkably, D.F. was not significantly different in mean inter-finger orientation error in either direct (D.F. = 4.32° versus mean control 3.02°,  $t(1)=5.59$ ,  $p > 0.05$  one-tailed) or pantomimed pointing

(D.F. = 11.11° versus mean control 6.60°,  $t(1)=4.18$ ,  $p > 0.05$  one-tailed). On inter-finger orientation, D.F. was profoundly impaired in pantomimed pointing (D.F. = 50.45 mm, control mean = 10.69 mm,  $t(1)=463.7$ ,  $p < 0.002$  one-tailed) but not in direct pointing ( $M=7.50$  mm, control mean = 7.72 mm,  $t(1)=-1.50$ ,  $p > 0.05$  one-tailed).

In spite of her poor accuracy in the pantomimed movements on two of our three measures, D.F. still showed a strong relationship between both the inter-finger distance and orientation in the terminal phase of the reaches and the actual target distance and orientation. The correlations between inter-finger distance and target distance were significant in both direct ( $r=0.98$ ,  $p < 0.001$ ) and pantomimed ( $r=0.82$ ,  $p < 0.001$ ) pointing conditions. Nevertheless this relationship in the pantomimed condition was not as strong as that seen in the controls (C.H. direct:  $r=0.99$ ,  $p < 0.001$ ; C.H. pantomime  $r=0.96$ ,  $p < 0.001$ ; C.L. direct  $r=0.98$ ,  $p < 0.001$ ; C.L. pantomime  $r=0.94$ ,  $p < 0.001$ ). Consistent with her overall orientation accuracy, D.F. performed as well as to he two controls for the relationship between terminal inter-finger orientation and inter-stimulus orientation in both direct (D.F.  $r=0.99$ ; C.H.  $r=0.99$ ; C.L.  $r=0.99$ , all  $p$ 's  $< 0.001$ ) and pantomimed pointing (D.F.  $r=0.97$ , C.H.  $r=0.99$ , C.L.  $r=0.98$ , all  $p$ 's  $< 0.001$ ).

We also had the opportunity to examine temporal coordination of this set of movements in D.F. and the controls. Because we recorded the time at which movement trajectory reached the Z threshold, the timing of her arrival at two targets could be compared to that of the controls. The mean absolute values of the temporal differences were slightly longer in D.F. than the controls (D.F.: 79 ms; C.H.: 23 ms; C.L.: 33 ms) and the two times were highly correlated in all participants, although less so in D.F. [direct  $r(23)=0.73$ ,  $p < 0.05$ ; pantomimed  $r(21)=0.98$ ,  $p < 0.01$ ] than in C.H. [direct  $r(24)=0.95$ ,  $p < 0.01$ ; pantomimed  $r(22)=0.89$ ,  $p < 0.01$ ] or C.L. [direct  $r(21)=0.98$ ,  $p < 0.01$ ; pantomimed  $r(21)=0.98$ ,  $p < 0.01$ ]. D.F.'s durations (right hand 709 ms, left hand 661 ms<sup>4</sup>) were slower than C.H. (right hand 446 ms, left hand 418 ms) and C.L. (right hand 490 ms, left hand 478 ms). There is a suggestion in these data that the difference between her two hands (48 ms) is larger than in the controls (C.H. 28 ms; C.L. 12 ms), although difference scores cannot be compared statistically without a larger control sample (Crawford & Garthwaite, 2005, 2007).

#### 4. Discussion

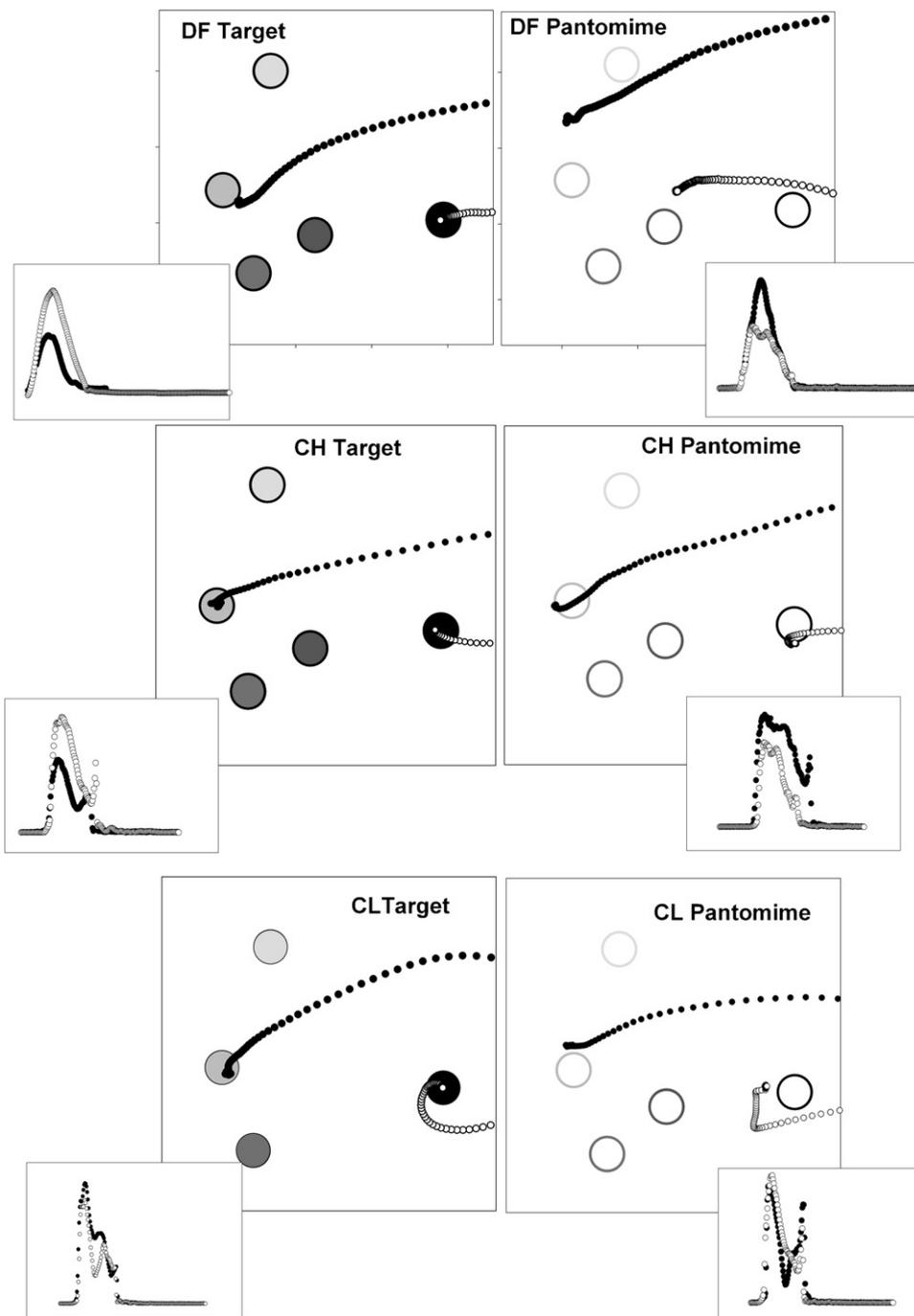
The current study extended our previous experiments on allocentrically versus egocentrically driven pointing in a patient with visual form agnosia. In spite of extensive work on pointing and grasping in D.F., her capacity to generate accurate bimanual movements, even in direct egocentric conditions was previously unknown.<sup>5</sup> We suspected that in the allocentric conditions of the pantomime task, neurologically intact participants could treat the two targets as a vector with a discrete spatial position (relative to the edges and/or centre of the square array), much like they can treat the entire array as a pattern which leads to their metrically accurate copying (Carey et al., 2006). This kind of strategy appeared to be unavailable for copying in D.F., so we hypothesized a heavy cost on bimanual movement accuracy in the pantomimed condition. This is indeed what we found (Figs. 3 and 5). She was

<sup>2</sup> Neurologically intact people make very accurate numerosity judgements for arrays of five or less without appearing to count them serially, a process referred to as "subitizing" (e.g. Trick & Pylyshyn, 1994). Observations in this study suggest that D.F. cannot subitize even arrays of only 3 targets.

<sup>3</sup> For direct reaching, D.F. right hand (rh) error = 13.4 mm, left hand (lh) = 10.3 mm (C.H. rh = 8.6 mm, lh = 8.8 mm; C.L. rh = 8.4 mm, lh = 9.4 mm). For pantomimed reaching D.F. rh = 32.9 mm, lh = 40.9 mm (C.H. rh = 15.9 mm, lh = 11.2 mm; C.L. rh = 11.5 mm, lh = 13.4 mm). Unfortunately the appropriate test of the differences between the two hands, using Crawford and Garthwaite's (2005) procedures for testing for a double dissociation in a single patient require  $n-2$  degrees of freedom which we do not have with our control sample of 2 participants.

<sup>4</sup> Although there is a suggestion of some left parietal damage in D.F. (James et al., 2003), in our previous unimanual pointing and grasping experiments D.F. always chose to point her right hand. Her good performance in those studies argues strongly against any apraxic or ataxic disturbance.

<sup>5</sup> M. Mon Williams, R.D. McIntosh and two of the authors are currently preparing a manuscript that describes some limitations in D.F.'s ability to grasp targets bimanually using the paradigm described by Bingham, Hughes, and Mon-Williams (2008).

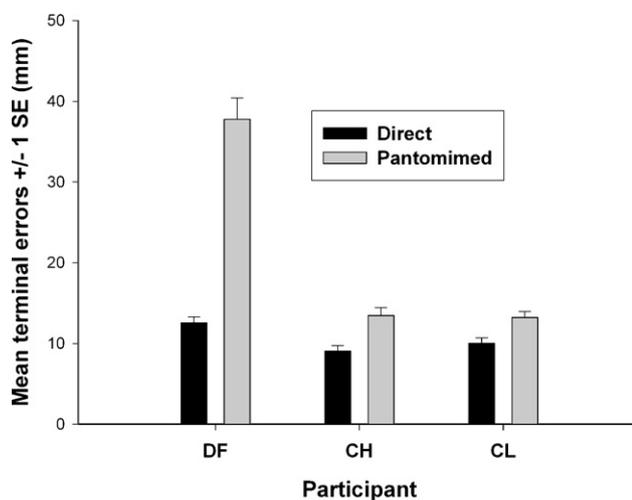


**Fig. 2.** Sample bimanual movements for the same target and pantomime arrays for D.F. (top panels) and control participants C.H. and C.L. Reaches directed to tokens on the stimulus array appear in the left column, pantomimed reaches to homologous positions on the blank array appear in the right columns. The associated velocity profiles for both fingers appear below each graph. Reaches to red (far left) and black targets (far right) were accurately performed by all three participants in the target trial. (Shading of the reach trajectories match the associated velocity profiles and not the required targets). Note that the reach deviation in control C.L.'s pantomime trial was not a late adjustment based on endpoint accuracy relative to the target (as she was reaching to a blank array).

significantly worse on both the terminal and distance error measures. However, she was (statistically, at least) unimpaired on the orientation error measure, even in the pantomimed pointing. Previously, we found that D.F. showed preserved orientation but not distance coding when two holes in a transparent disc had to be grasped using forefinger and thumb (Dijkerman, Milner, & Carey, 1998). In the present study, preservation of inter-stimulus orientation in pantomimed pointing suggests that D.F. may be able to prepare bimanual movements to the specified pair on the stimulus array and then translate those movements to the pantomimed array. As in the disc grasping study, in this translation

process orientation is preserved but inter-stimulus distance is not (Fig. 5).

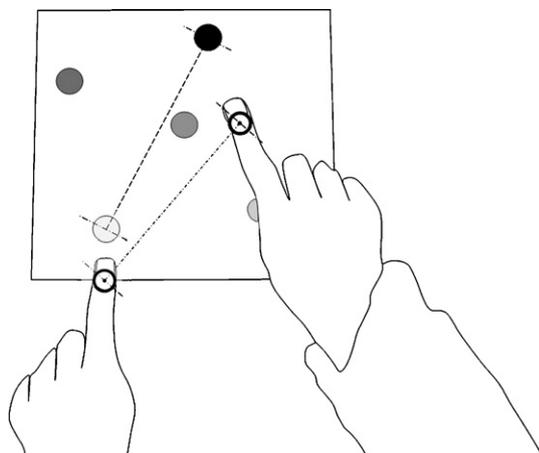
Although little is known about the attentional and eye-movement-related processes that allow for accurate bimanual movement, the yoking of the two hands in terms of onset and end times has been the subject of considerable research (Wiesendanger, Kalzuny, Kazennikov, Palmeri, & Perrig, 1993). D.F. shows some evidence of coupling of the two hands. Although the terminal times of her two fingers are less well correlated than in the controls, the average difference of 79 ms between her two hands (particularly given her longer overall movement times) does not suggest



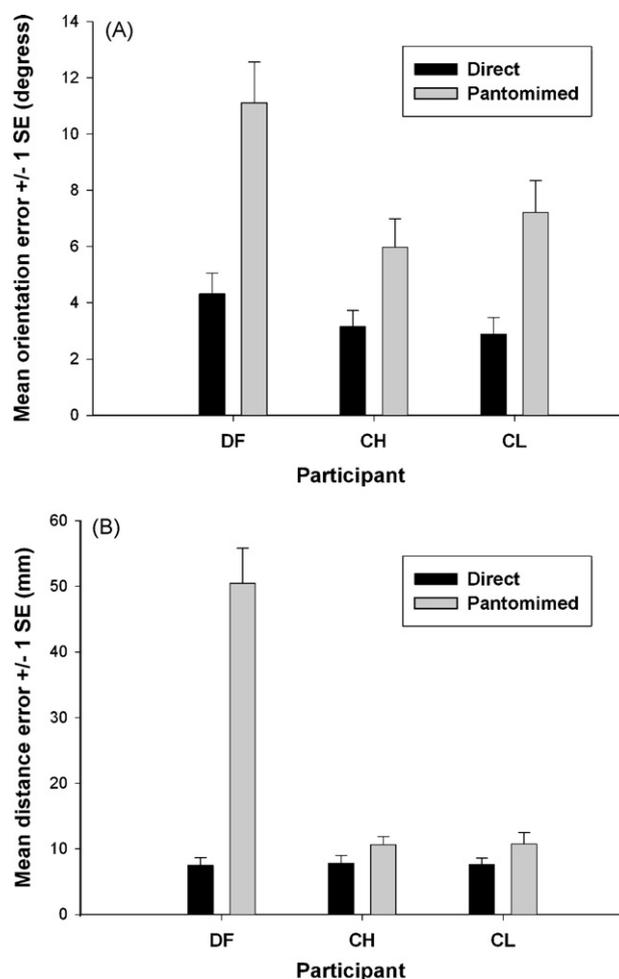
**Fig. 3.** Mean terminal error for target and pantomimed pointing. X and Y coordinates were taken from a point 50 ms before the movement was less than 1 cm above the table surface.

an obvious serial strategy, whereby one hand arrives at its target well in advance of the other, allowing for overt or covert attention resources to be re-deployed to the other hand or target (cf Riek et al., 2003). D.F. seemed to be planning and executing bimanual movements in a manner similar to that of controls.

In these free viewing conditions with constantly visible targets, D.F. seems capable of coding the categorical relationships of any two tokens with some accuracy; for example, her copies tend to be quite accurate in terms of the left to right and bottom to top ordering of the tokens (Carey et al., 2006; Murphy et al., 1998). Observation of her performance suggests that she can use this sort of strategy for any two target positions in spite of her poor ability to compare the patterns of a target array and a copy. The array sizes we used in this study were small, therefore categorical (above, below, left, right) codes could account for hand landing orientations that are correlated with actual inter-stimulus orientations. Nevertheless we have to acknowledge that the near perfect correlations in direct, and especially pantomime conditions (as well as preserved orientation accuracy) seem rather high for this sort of explanation. She was much less sensitive to the metric inter-stimulus distances than



**Fig. 4.** Comparing terminal inter-finger with inter-target distance and orientation. A sample movement from a control participant was digitized and converted into a line drawing. The inter-finger distance is specified by a dot-dashed line ending with the middle of each finger's IRED (open circles). The inter-target distance and orientation are depicted with the dashed line. A direct reach is depicted; for pantomimed reaches calibration coordinates for calculating inter-target distance and orientation were obtained by placing the direct array on top of the blank pantomimed array.



**Fig. 5.** Mean orientation and distance errors for D.F., C.H. and C.L. (A) Orientation errors were defined as the unsigned difference (absolute value) of each participant's inter-finger orientation (before contact with the table surface) with the orientation of the targets. (B) Distance errors were calculated as the unsigned difference between inter-finger distance (before contact with the table surface) and inter-target distance. D.F. is only significantly impaired for distance errors in the pantomimed pointing condition.

the controls in the pantomime task, as seen in both her terminal and distance error data and lower correlation between inter-finger distance and inter-stimulus distance.

Her relative successes in the pantomimed trials have been the subject of some discussion by us in the unimanual movement and copying tasks used in our previous studies. We have known for some time that, under certain conditions, D.F.'s perceptual responses can be cued by the explicit preparation of a manual act. For example, Murphy et al. (1996) required D.F. to reach out and grasp a specified target from a rectangle and a square. They found that she selected the target correctly more often than when she simply responded left or right (the perceptual task). On close inspection of video-recordings, they found evidence of late trajectory corrections for many of her reaching trials. These data suggest that D.F. is somehow able to use a motor-related signal to inform her choices on this task. Two of us (Dijkerman & Milner, 1997) examined D.F.'s abilities to copy oriented lines (a "perceptual task" in that the response, as in pantomimed pointing, was distant from the visual stimulus driving it) under various conditions. They found that asking her to make her drawing response without delay greatly worsened her performance, and suggested that D.F. needed time to use an internal self-cueing strategy whereby sensorimotor preparation could prime an apparently "perceptual" choice. It may be that in the

present study inter-manual orientation lends itself more readily to visuomotor representation of this kind than does inter-manual distance. Such an account also suggests (albeit tentatively) that a bimanual encoding strategy is available to D.F. for this task, albeit of a sensorimotor cross-cueing variety. For example, a “motor image” of making an oriented movement between the two stimuli might be rather similar to the motor imagery that Dijkerman and Milner (1997) suggested D.F. might have been using to mediate her successful orientation copying performance.

It should be noted that the above finding of Dijkerman and Milner (1997) on delayed copying is quite different from the effects of delay on D.F.’s reaching and grasping, where performance declines markedly (e.g. Goodale, Jakobson, & Keillor, 1994; Goodale, Westwood, & Milner, 2004; Milner et al., 1999). In the pantomimed trials reported here and in Carey et al. (2006), the task required participants to extract spatial information from the stimulus arrays, some of which might decay during the time between stimulus inspection and the pantomimed response (which was controlled by the experimenter providing a countdown before a go signal). Her poor performance on pantomimed pointing measured by terminal and distance errors suggests that a perceptual strategy available to the controls was not available to her. As noted by Murphy et al. (1998) and Carey et al. (2006), D.F.’s slavish reproductions of the arrays relative to controls suggest that she cannot code the arrays as a “gestalt” which can be carefully compared to the targets.

Her high levels of skill in these bimanual trials surprised us to some extent. There are hints in the bimanual aiming literature that in some tasks at least, serial strategies are used in bimanual aiming (e.g. Riek et al., 2003). Honda (1982) suggests that there are lateral biases in processing, with the target being approached preferentially by the dominant hand in relatively unconstrained conditions. Remarkably, there seems to be no previous experiment where the kinematics of bimanual movements have been examined while participants were required to fixate a central non-target position. Assuming participants could manage this without catastrophic effects on accuracy, the possibility of covert asymmetries even with overt attentional shifts remains relatively under-explored. Diedrichsen, Nambisan, Kennerley, and Ivry (2004) suggest that the visual control for the two hands can approach complete independence, as the hands can independently adjust for perturbations to both targets within the same trial. Clearly different task constraints within specific grasping (e.g. Bingham et al., 2008) or reaching tasks, will have profound effects on movement synchrony or asynchrony (as will the criteria that different laboratories use for describing movements as relatively synchronous or asynchronous). In fact, the type of bimanual pointing trials that we have used here is unusual in that the targets were specified well in advance of the required reach, and in that participants were not just allowed to overtly attend to both targets repeatedly before a go signal; they were actively encouraged to do so. And yet, spatial positions for each target pair varied from trial to trial, although participants reached to specific targets on more than one occasion for all of the arrays. These task differences may not be trivial. For example, Diedrichsen, Hazeltine, Kennerley, and Ivry (2001) found that directly cued target pairs (such as suddenly appearing targets) may result in more synchrony between movements by each hand compared to target pairs that are cued more abstractly (in ways arguably comparable to the verbal instruction of target pairs used in this study).

As noted by Carey et al. (2006), further examination of D.F.’s limits on bimanual direct and pantomimed pointing are called for. Although it is difficult to record her eye movements (due to the characteristics of her eyelids rather than any feature of her neurological difficulties), touch-screen technology could allow for bimanual tasks to be carried out in a more ‘open loop’ fashion. For example, controlling presentation times of the direct array and requiring a more rapid response to the pantomimed array could be

used to eliminate any sensorimotor cueing effects. Changes in shape of the two arrays might help demonstrate the use (or failure to use) metric cues about stimulus positions relative to the edges of direct pointing space. Limitations of parallel versus serial processes could be addressed in a direct aiming task by using staggered stimulus presentations. The spatial intolerance of her sensorimotor responsiveness could be investigated with smaller displacements than the current distance between the direct and pantomimed arrays.

## 5. Conclusions

The present data confirm the difficulties that D.F. has with allocentric visuospatial tasks, even when the response allows her to make ballistic aiming movements. While the deficit is not complete, it should be borne in mind that D.F.’s ventral stream lesion is likewise incomplete, being concentrated largely in the shape-processing area LO (James et al., 2003).

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