

Proprioception in motor learning: lessons from a deafferented subject

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Abstract Proprioceptive information arises from a variety of channels, including muscle, tendon, and skin afferents. It tells us where our static limbs are in space and how they are moving. It remains unclear however, how these proprioceptive modes contribute to motor learning. Here, we studied a subject (IW) who has lost large myelinated fibres below the neck and found that he was strongly impaired in sensing the static position of his upper limbs, when passively moved to an unseen location. When making reaching movements however, his ability to discriminate in which direction the trajectory had been diverted was unimpaired. This dissociation allowed us to test the involvement of static and dynamic proprioception in motor learning. We found that IW showed a preserved ability to adapt to force fields when visual feedback was present. He was even sensitive to the exact form of the force perturbation, responding appropriately to a velocity- or position-dependent force after a single perturbation. The ability to adapt to force fields was also preserved when visual feedback about the lateral perturbation of the hand was withdrawn. In this experiment, however, he did not exhibit a form of use-dependent learning, which was evident in the control participants as a drift of the intended direction of the reaching

movement in the perturbed direction. This suggests that this form of learning may depend on static position sense at the end of the movement. Our results indicate that dynamic and static proprioception play dissociable roles in motor learning.

Keywords Proprioception · Motor control · Deafferentation · Force field learning

Introduction

Proprioception is a collective term that refers to non-visual input that tells us where our body is in space. Proprioception has an important function in normal motor control and motor learning. It is well documented that patients who have suffered loss of proprioception make significant errors in movement (Forget and Lamarre 1987; Rothwell et al. 1982; Sainburg et al. 1995; Sanes et al. 1985). Proprioception can be further divided into static versus (active or passive) dynamic proprioception (Fuentes and Bastian 2010; Gritsenko et al. 2007; Jones et al. 2010). Static refers to sensing limb position while stationary, whereas dynamic proprioception involves the estimation of limb position and velocity during either a self-generated active movement or during a passive displacement.

Proprioception relies on various types of mechanoreceptors. Muscle spindle receptors signal both the length of the muscle and the rate of change, hence contributing to both static and dynamic proprioception (Edin and Vallbo 1990; Matthews 1933). These receptors are innervated by large, myelinated primary afferent fibres (A α) (Gilman 2002). Golgi tendon organs respond to muscle tension (contraction) and are principally active during voluntary movements (Houk and Henneman 1967; Prochazka and Wand

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1980). These are subserved by large, myelinated group Ib, A α fibres. In addition, there are also receptors found in the joint capsules. These are predominantly innervated by small afferent fibres signalling nociception, as well as mechanoreceptors signalling flexion or extension. Finally, stretch-sensitive receptors in the skin, relayed through large myelinated afferents, also play a role in signalling proprioceptive information (Aimonetti et al. 2007).

While previous work has shown that these subtypes of proprioception have different properties in motor control (Adamovich et al. 1998; Fuentes and Bastian 2010; Gritsenko et al. 2007; Ostry et al. 2010; Wong et al. 2012), it is unclear how these different channels contribute to motor learning. To test this, we examined the motor behaviour of a deafferented subject (IW), who has lost large myelinated sensory fibres below the neck (Cole and Katifi 1991; Cole and Sedgwick 1992; Cole et al. 1995). As expected, he was significantly impaired in a static proprioceptive task. However, his ability to detect the direction of a force perturbation to an active, ongoing movement was remarkably preserved.

This pattern of deficit and performance allowed us to ask what role active, dynamic, and static proprioception plays in error-driven force field adaptation and use-dependent learning. We first tested whether IW would be able to adapt normally to force fields, and specifically whether he would be able to shape his adaptive response according to whether a position- or velocity-dependent force field was presented (Sing et al. 2009). We also studied him under conditions where visual information about the lateral perturbation was withdrawn to test whether force field learning was preserved without vision.

This experiment allowed us to test whether dynamic or static proprioceptive information underlies use-dependent learning. When lateral deviations of the hand from the target cannot be seen and are not penalised as an error, normal participants alter their intended reaching movements in the direction of the perturbation (Diedrichsen et al. 2010). We hypothesised that this form of learning may rely on a static sense of position and therefore predicted that IW would not show the normal response seen in healthy individuals.

Materials and methods

Deafferented subject

The deafferented subject IW (60 years old at last time of testing, left-handed) lost the sense of touch and proprioception as a result of an acute onset sensory neuronopathy caused by an autoimmune response to a viral infection when he was 19 years old (Cole and Sedgwick 1992). Neurophysiological tests have confirmed the loss of large

myelinated fibres below the neck (Cole and Katifi 1991), though he has regained good motor control with cognitive control and with the use of vision and muscle power is normal. He has perception of pain, heat, and cold, suggesting that small fibres are intact (Cole et al. 1995).

Participants

A total of 16 age-matched control participants were also tested, with two self-reported left-handers and the remainder right handed. Nine volunteers participated in the static proprioceptive test (six males, mean age 56 ± 10 years), and six different participants took part in the active proprioceptive test (three males, mean age 55 ± 12 years); these six plus an additional participant completed the force field adaptation experiments (four males, mean age 54 ± 12 years). Experimental and consent procedures were approved by the University College London Ethics Committee.

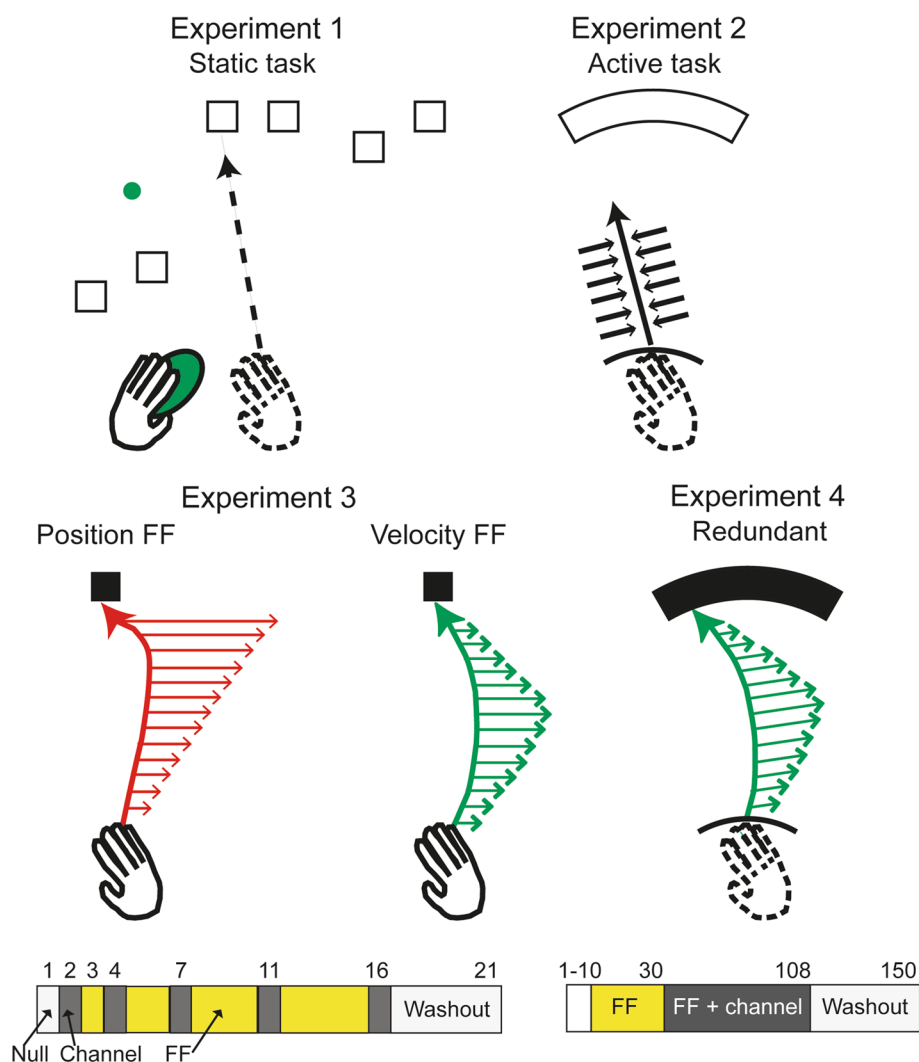
Apparatus

Participants sat in front of a virtual environmental set-up, with their head on a forehead rest. They made 15-cm reaching movements to a single target with their dominant hand while holding onto a robotic device. The static proprioceptive task was performed using a robotic device that was equipped with an armrest, which brought the elbow into the same plane as the hand. The remainder of the experiments was performed on a device without elbow support. Both devices recorded the position of the hand with a sampling frequency of 200 Hz. A monitor displayed a white square ($0.5 \text{ cm} \times 0.5 \text{ cm}$) indicating the start position. The screen was viewed via a mirror, such that participants did not have direct vision of their arm, but sometimes received continuous and calibrated visual feedback of their hand position either via a 0.3-cm-diameter white cursor circle or via an arc (see individual experiments below).

Experiment 1: Static proprioception

To measure the participants' static proprioceptive sense, subjects held onto the robotic manipulandum with their dominant hand and were asked to refrain from making any active movements. The robotic device then moved the participant's hand to an unknown position, while direct vision of the hand and arm was prevented, and no visual feedback was displayed on the screen. When the participant's hand was within 0.5 cm of the target position, a cursor was displayed at a random location on the screen (Fig. 1). By moving the cursor with a mouse held in their non-dominant hand, the participant was asked to match the cursor location to the location they felt their target hand to be. We tested

Fig. 1 Experimental paradigm. Experiment 1: In the static proprioception test, participants' right hand was passively moved to one of six randomly chosen locations. There was no visual feedback about the position of the hand (*dashed line*). At the end of the movement, the participant indicated the felt position of the hand with the left hand via a cursor controlled by a mouse. Experiment 2: In the active proprioceptive task, we asked subjects to reach to an arc target without vision of their hand or arm and with cursor feedback provided via an arc cursor. At the end of each reach, we asked subjects to respond as to whether they had been pushed to the right or left. Experiment 3: Participants were exposed to position- or velocity-dependent force fields for short blocks of 21 trials with full visual feedback (*solid line* for hand). Experiment 4: Participants adapted to a velocity-dependent force field in long blocks of 150 trials with task-irrelevant visual feedback



six locations (two at ± 1.3 cm either side of the midline, two at the bottom left of the workspace, and two at the top right of the workspace) presented randomly 25 times (total 150 trials divided into six blocks). IW and the one other left-handed participant performed the task with their left hands, and the locations of the targets were mirror-reversed in the y-axis. The sequence was constrained such that each location was located in a different region of the workspace than the last one. Because the sequence was otherwise random, participants needed to rely on a sense of static position at the end of the movement. Possible dynamic information of change in hand position was only informative in combination with accurate information about the starting location of the hand, which was not provided to the participants. The arm was supported such that the elbow and wrist were in the same horizontal plane.

We analysed the endpoint errors by plotting the 95 % confidence ellipse of the responses for each target and for each subject. To compare performance quantitatively, we calculate the SD of the responses in each direction and then

averaged these across *x*- and *y*-directions. IW's scores were expressed as a *z*-score relative to the mean and standard deviation of the control group's performance.

Experiment 2: Active proprioception

To quantify proprioception to perturbations during active movements, we asked subjects to reach straight ahead, while their reach was deviated by the robotic device either to the left or to the right (Fig. 1). They had no vision of their hand or arm and no visual feedback about their movement direction. On each trial ($n = 105$ in two blocks), we constrained the hand to move an oblique trajectory via a force channel, and when the participant reached the target, we asked them whether they had ended up to the left or to the right of midline. However, we presented an arced cursor that indicated the distance moved by the hand and an arced target that signalled the required movement amplitude. Both the target and the cursor were a 60° segment of a circle, centred on the starting location of the movement. Therefore, participants only had feedback

about how far their arm had reached and no feedback about the endpoint or angle of their reach. We tested 21 angles for the channel that deviated the hand movement (0° , $\pm 3^\circ$, $\pm 6^\circ$, $\pm 9^\circ$, $\pm 15^\circ$, $\pm 20^\circ$, $\pm 25^\circ$, $\pm 30^\circ$, $\pm 35^\circ$, $\pm 40^\circ$, $\pm 45^\circ$). Each angle was tested five times, and the presentation of the trials was randomised. We analysed the responses using logistic regression. The responses (left/right) were categorised as zeros (left) or ones (right). We first fitted the data using the channel angle and an intercept, which gave two regression weights. The regression weight for the channel angle expresses the steepness of the curve, from which we calculated the interquartile range (IQR) as a measure of discrimination ability: the difference in angle for which the participants made 25 % rightward or 75 % rightward responses. To determine how the force produced in the channel influenced the response of participants, we also added the force measured at 200 ms as a third regressor into the logistic model.

Experiment 3: Force field perturbation

In this experiment, we tested how participants adapted their reaching movements to position- and velocity-dependent force fields. At the beginning of each trial, participants moved the cursor into the start box. When the target appeared 15 cm from the start position, participants were instructed to move the cursor to the target in the straight-ahead direction and stop at the target (Fig. 1). In all experiments, the arm was pushed back to the start without visual feedback—therefore, they should have had no knowledge of results from visual information. Movements had to have a peak speed between 55 and 80 cm/s. Furthermore, the movement needed to stop within 800 ms at a distance of less than 0.65 cm from the centre of the target. If all these criteria were met, the target turned red and exploded, and participants scored a point. If the movement was not fast enough or was not completed within 800 ms, the target turned blue or pink; if participants moved too fast, the target turned yellow; if participants moved at the right speed but stopped the movement too far from the target, the target turned green. However, all trials were included in the analysis, and only trials where participants moved less than half the distance to the target, or showed a large deviation ($>80^\circ$) in the initial movement direction were excluded.

On force field trials, participants were exposed to a dynamic force field, exerted orthogonally to the actual movement direction. The force (N) could depend either on the position (in cm) or on the velocity (cm/s) of the hand.

$$\begin{bmatrix} \text{Force}_x \\ \text{Force}_y \end{bmatrix} = C_p * s_1 * \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} * \begin{bmatrix} \text{Position}_x \\ \text{Position}_y \end{bmatrix} + C_v * s_2 * \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} * \begin{bmatrix} \text{Velocity}_x \\ \text{Velocity}_y \end{bmatrix}$$

The position-dependent force field ($C_p = \pm 1$, $C_v = 0$) pushed the hand either to the left or to the right and increased monotonically from the start of the movement. The velocity-dependent force field ($C_p = 0$, $C_v = \pm 1$) acted either in a clockwise or anticlockwise direction relative to the movement direction and reached its highest force at peak velocity (Fig. 1). We chose the coefficients s_1 (0.225 N/cm) and s_2 (0.075 Ns/cm), to achieve a peak force of ~ 4 N on force field trials.

To probe the state of the adaptation response, we used force-channel trials that were inserted throughout the blocks. During channel trials, the robot applied a spring-like force in the x -direction (6000 N/m), which forced the hand onto a 0° trajectory from the starting position. No force was applied on the y -direction. To reduce vibration, we also applied a small viscous damping force (75 Ns/m). If participants expected to be pushed by a force field, they would exert a compensatory force into the wall of the channel during the movement.

Following 80 practice trials (not used for analysis), participants were exposed to eight short blocks of either the position- or velocity-dependent force field in either a clockwise or anticlockwise direction. These four different conditions were presented in randomised order. Each condition consisted of a 21-trial blocks: one null trial, one channel trial, one force field trial, one channel trial, two force field trials, one channel trial, three force field trials, one channel trial, four force field trials, one channel trial, and five null trials (Fig. 1). During all trials, subjects had full vision of their hand location via a cursor on the screen.

Experiment 4: Force field adaptation without visual feedback of movement direction

In this experiment, we withdrew all visual feedback about the lateral deviation of the hand. The target was a wide circle segment rather than a square (Fig. 1), and the cursor was not a dot but also a circle segment centred on the starting point of the reach, which expanded as the participant reached towards the target. It therefore displayed the extent of the reach, but gave no information about the lateral position of the hand. Subjects were instructed that they could reach to any angle within the arc target as long as the extent of their reach brought the cursor within the target. Therefore, lateral deviations of the hand were not task-relevant (Diedrichsen et al. 2010).

The experiment consisted of two blocks (one adaptation to a clockwise force field and one anticlockwise, with the order counterbalanced across participants), each 150 trials long, consisting of 10 null trials, 30 velocity-dependent force field trials with no channels, 68 force field trials of which 27 were randomly presented channel trials, and 42 null trials with 15 random channels. The angle of the 27

channel trials in the latter stages of adaptation and in the washout phase was determined by the average endpoint of the participant once they had adapted to the force field. This angle was found from the mean endpoint angle over 15 trials. Each block was split into three parts, and participants could have a short break in between parts.

Force field analysis

For the force field experiments, we were primarily interested in the force with which participants pressed into the force channel. To quantify the strength and time course of the force responses, we regressed the x -force (F_x) of each individual trial from 300 ms before movement start until movement end against the y -position (P_y) and the y -velocity (V_y) of the same trial:

$$F_x - \bar{F} = b_1 s_1 P_y + b_2 s_2 V_y + \varepsilon$$

Before the regression, we subtracted a common baseline (\bar{F}) from each trial, which was calculated from the average force profile of the channel trials when the target was at 0° and the channel forced the hand on a 0° trajectory. These trials came from the practice blocks and the pre-adaptation and post-washout channel trials in experiments 3 and 4. The multiple regression model therefore did not contain an intercept. The position and velocity traces were scaled by factors s_1 (0.225 N/cm) and s_2 (0.075 Ns/cm) to convert them into units of force. Thus, the two resultant regression coefficients (b_1 and b_2) express the adaptation relative to the strength of the position- and velocity-dependent force fields. Therefore, a regression coefficient of 1 indicates a force that is exactly equal and opposite to the imposed force field, i.e. it implies that the system fully adapted to the force field. Since there was no significant difference between the left and right acting force fields, we sign-reversed the regression coefficients for leftward force fields and then averaged over the left/right trials of

the same condition. These regression coefficients are first plotted in (position, velocity) coefficient space. The origin represents no adaptive response, and full adaptation to the pure velocity- or position-dependent force fields would be evidenced by position/velocity regression coefficients of (0,1) and (1,0).

Results

Static proprioceptive sense is impaired in the deafferented subject

We first aimed to establish the level of static proprioceptive impairment in IW compared to the controls. Figure 2a shows the results from a single representative participant performing the task. This participant had a tendency to report the location of their hand to be closer to their body and more to the right, and their mean signed error (Euclidean distance of the reported hand position to the true hand position) between actual hand position and indicated hand position was 2.3 cm. IW's responses are shown in Fig. 2b. His responses for the different hand locations were highly overlapping in space, indicating a lack of specificity for the target locations. His error was slightly larger for the central locations (mean = 9.01 cm) compared to the targets at the bottom left (mean = 7.55 cm) and the top right (mean = 8.34 cm), but a one-way ANOVA showed no significant effect of target location ($F = 1.22$, $p = 0.250$). Comparing the spread of responses, IW had mean SD of 5.6 cm in the x -direction and 3.6 cm in the y -direction. IW's SD lay outside of the range of the normal controls in the x -direction ($z = -6.03$, $p < 0.001$) but not in the y -direction ($z = -1.2$, $p = 0.2297$). This difference may be the result of a range effect (Stevens 1957)—the observation that participants tend to respond in the middle of a limited scale. In our experiment, the screen used was longer in the x - than

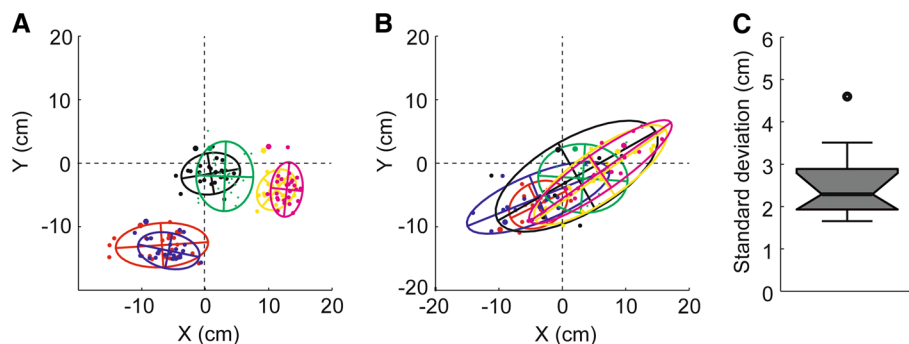
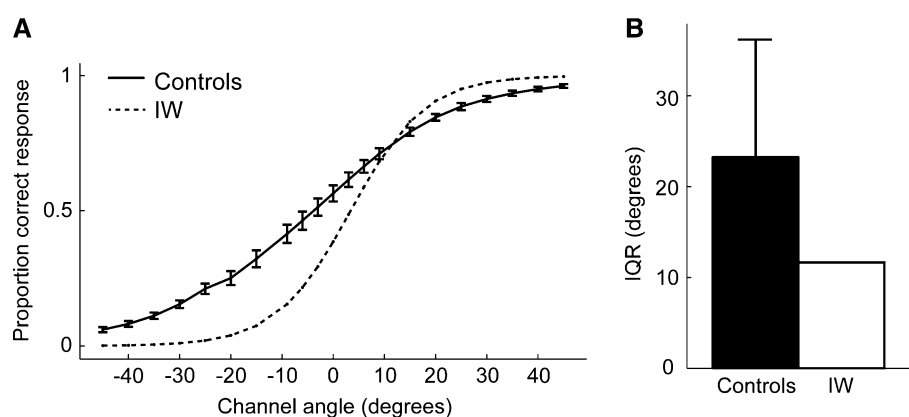


Fig. 2 Results of static proprioception test. **a** The responses (small dots) and 95 % confidence ellipses of a single control participant performing the static task for the six targets. **b** IW's responses were

highly overlapping in space, indicating the lack of specificity for the target locations. **c** Box plot showing the average SD of the endpoints for the control participants and IW (black circle)

Fig. 3 Results of dynamic proprioception task. **a** The mean psychometric curve obtained from the logistic regression of control participants' responses in the active proprioceptive task (solid line) and the same plot for IW's responses (dashed line). **b** The performance in the active task was quantified by the IQR, showing that the control group (black bar) had a larger IQR indicating worse performance compared to IW (white bar)



in the y-direction, providing a reference frame for the responses. Alternatively, this may relate to the observation in a previous study by van Beers et al. (1998). They showed that in a similar proprioceptive static task, localisation was more precise in the radial compared to the azimuthal direction. Averaged over the two directions, the spatial standard deviation for IW lay clearly outside of the range of the control group ($z = -3.21$, $p = 0.0013$, Fig. 2c). Interestingly, in the static task, we find that the force applied to move the hand to the target was significantly larger for IW (13.3 N) than the control group (6.88 N, $z = 3.16$, $p = 0.0016$), indicating that he is likely to stiffen his arm more than the controls. Hence, this proprioceptive task demonstrates that IW has an impaired sense of the static location of his arm when it is passively moved to an unseen location.

Active proprioception is preserved in deafferented subject

Next, we considered whether dynamic active proprioception was also affected in IW. Based on the previous work showing that this patient had lost all large-fibre proprioceptive sense in his upper limbs (Cole and Katifi 1991; Cole and Sedgwick 1992; Cole et al. 1995), a similar deficit to that seen in the static task might have been expected. Participants executed point-to-point reaching movements without visual feedback, during which tilted force channels deviated their arm sideways. After each movement, participants reported whether they had been deviated to the left or to the right. Based on the participants' responses, we constructed individual psychometric curves using logistic regression (see "Materials and methods").

Figure 3a (solid line) shows the average psychometric curve for the control participants (after fitting each participant individually) and the same plot for IW (dashed line). IW's curve is steeper than the control's, indicating that he performed better on this task. To quantify this, we then computed the angle range which would produce a 25–75 % change in correct identification, the interquartile range

(IQR, Fig. 3b). The mean IQR (based on the individual IQR per control participant) was $48.6^\circ (\pm 44.4^\circ)$ and for IW was 16.4° , which demonstrates his better performance but did not differ significantly ($z = -0.725$, $p = 0.468$).

One possible reason for the poorer performance of control participants may have been a response bias that we observed in the control participants' data, presumably induced by the force that they sensed on their hand in the channel. Of course, the lateral force correlated highly with the direction of the channel—i.e. for a rightward pointing channel, the participants experienced a rightward pointing force. However, the correlation was not perfect, presumably because the order of the channels was random and participants adapted on a trial-by-trial basis to these tilted channels (Diedrichsen et al. 2010). Hence, the correlation between the angle of the channel and experienced force was only $r^2 = 0.848$. When we used the force as an additional variable in the design matrix for the logistic regression, we found that control participants were biased by the force that they exerted over and above the physical angle of the channel. The regression weight for the channel force was significantly less than zero (mean = -0.22 , $t(5) = -4.34$, $p = 0.007$), meaning that even in a straight channel, participants were more likely to respond that they were pushed to the left if they produced a leftward force. In contrast, IW did not seem to show the same bias, his channel force regression weight was slightly greater than zero at 0.171 , which differed significantly from the controls ($z = 3.12$, $p = 0.002$). This indicates that the bias in the normal participants arose from a discrepancy between the direction of the force that they exert and the direction that they were pushed in. IW seemed not to be influenced by this bias.

Force field learning with vision is not impaired in the deafferented subject

The dissociation between static and dynamic active proprioception in IW allowed us to test the importance of

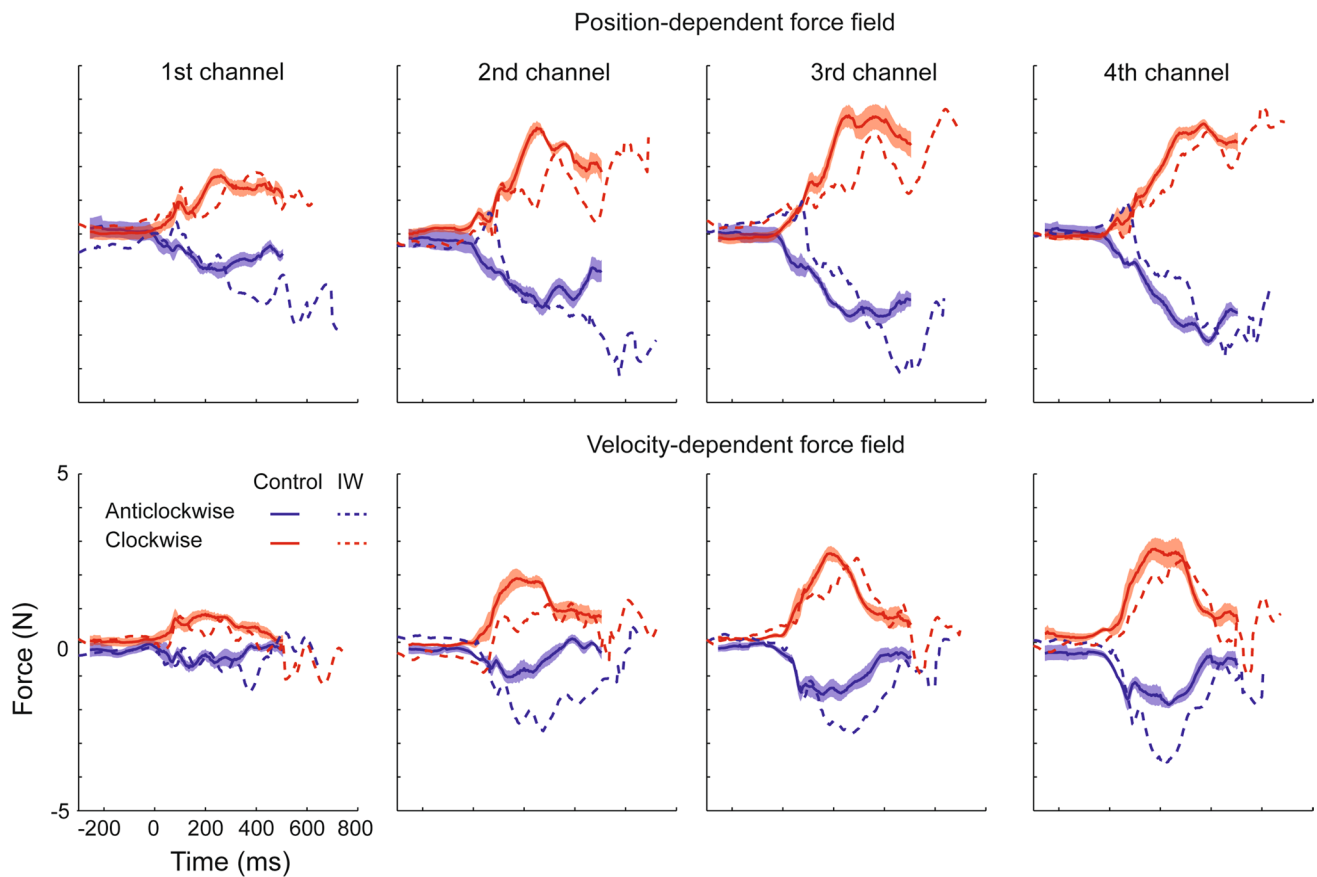


Fig. 4 Results of Experiment 3. During adaptation to clockwise (red) and anticlockwise (blue) force fields, the amount of adaptation was quantified by the force exerted in the channel trials as shown here for controls (solid) and IW (dashed). Participants initially respond

to a force which was made up of a mixture of position and velocity components in both types of force field (first channel), but this force becomes shaped to match the applied perturbation as participants adapt (colour figure online)

these modes of proprioception when adapting to a novel perturbation. Therefore, we let participants adapt to short blocks of either a position-dependent or a velocity-dependent force field. We hypothesised that with visual feedback of the hand, IW may be able to correct for the perturbation, but would be unable to shape the adaptive response appropriately to account for the shape of the applied force field, as he is missing detailed proprioceptive information. Participants had visual feedback of their hand position via a cursor at all times. We measured the amount of adaptation by the force exerted in channel trials. As previously shown (Sing et al. 2009), we found that participants initially responded with a force that was a mixture of position- and velocity-dependent components (Fig. 4). As adaptation progressed, the shape of this response became better matched to the applied perturbation, such that, in the position-dependent force field, more force was applied at the end of the trial, and in the velocity-dependent force field, more force was applied in the middle of the trial. This can be quantified by the path of the regression coefficients of the produced force against velocity and position

(Fig. 5, see “Materials and methods”). The path in adaptation space began by a step towards the diagonal and subsequently curved towards the appropriate axis. We found that IW performed similarly to the control subjects. Although his adaptation path in the position-dependent force field was less biased towards the diagonal at the start of adaptation (angle = 6.90° as compared to controls with 25.7°), this difference was not significant ($z = -1.24$, $p = 0.216$). Furthermore, the average angle of all his trials (for channel number >0) was 7.45° , and this was significantly different to zero ($t(38) = 2.4$, $p = 0.021$). Therefore, IW was able to adapt to force field perturbations, not simply by changing his motor plan to aim to a different location, but by shaping the force he exerts against the force field in a temporally specific manner. Note that IW’s baseline performance (during the practice trials without perturbations) was largely matched to the control group in mean peak speed, points gained, and movement time; however, his absolute endpoint accuracy error was increased compared to controls (1.49 cm compared to 0.81 cm), and this difference was significant ($z = 4.22$, $p < 0.01$). Therefore, IW’s

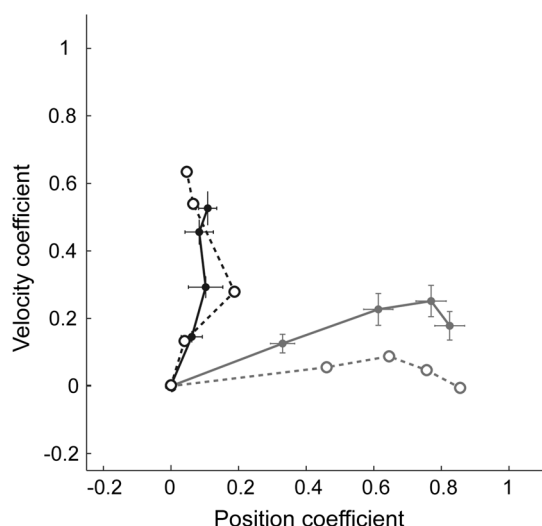


Fig. 5 Force adaptation in Experiment 3, plotted as position and velocity weights for the position-dependent force field (grey) and the velocity-dependent force field (black) blocks. Adaptation curves were biased towards the diagonal and then curved towards the appropriate axis. IW (dashed lines) performs similarly to the control subjects (solid lines) and is able to shape his responses appropriately to the applied force field

ability to adapt differentially to two different dynamic conditions clearly demonstrates his preserved ability to deal with dynamic loads, not simply relying on a stereotypical adjustment for perturbations in one direction.

Force field learning without task-relevant visual feedback

We next looked at the case when no visual feedback in the task-relevant dimension was given. Subjects reached to an arc target, visual feedback was given by an arc cursor, and

reaches were rewarded based on the accuracy of the reach extent alone. In a previous study (Diedrichsen et al. 2010), participants exhibited two effects in this experimental paradigm. First, they adapted to the force field as expected from normal error-based learning. Secondly, the intended endpoint also drifted in the direction of the force field. For example, if they reached normally to 0° within the arc when a clockwise force field was applied their movement would terminate at $+20^\circ$. This was partly due to participants not correcting for the lateral deviation (as it is task-irrelevant). A more important factor, however, was that the participants also shifted their desired endpoint in the direction of the force field. This was demonstrated by applying force channels that deviated the hand to the left or right of the average end position (Diedrichsen et al. 2010). In the end of the movement, participants would push towards the new end position, indeed confirming that this was the planned final position of the hand.

We hypothesised that these changes are driven by sensing the location of the movement endpoint using proprioception. Because the movement was generally successful, as the lateral deviation is task-irrelevant, participants may adjust their desired endpoint in this direction. With his strong impairment of static proprioception, we predicted that IW would not exhibit these effects.

Indeed, we found that the endpoints of IW's movements after adaptation to a velocity-dependent force field were much closer to his original endpoint than for control subjects (Fig. 6a). The change from baseline in the angle of the overall movement (start point to endpoint), averaged across clockwise and counterclockwise force fields, was $17.6^\circ \pm 7.59^\circ$ for controls, but 2.70° for IW, a significant difference, $z = -1.96$, $p = 0.050$. Also, IW made large online corrections when perturbed, as can be seen in the sharp hooks in the end of the trajectory. To quantify this

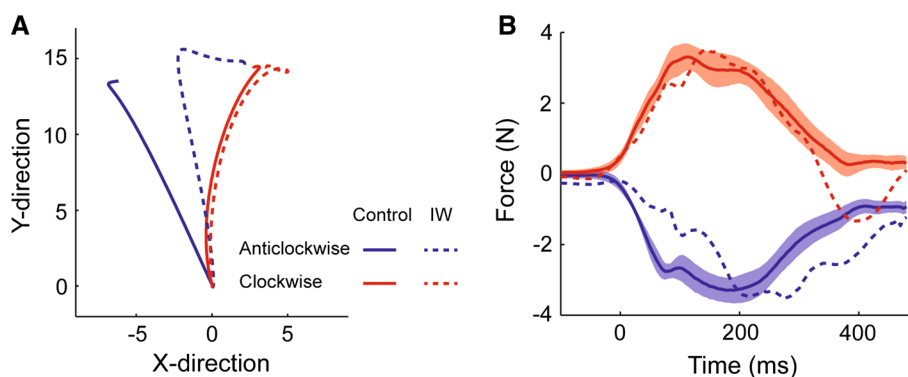


Fig. 6 Results of experiment 4. **a** Average trajectory for a clockwise (blue) or anticlockwise (red) perturbing force field. The mean trajectory across control subjects (solid lines) demonstrates that they shifted their endpoint in the direction of the applied force field. In contrast, IW (dashed lines) corrected more with the endpoints

remaining closer to the midline. **b** The channel forces (shading indicates between subject SE) once subjects had adapted to the force field show that the control subjects (solid line) show a velocity-dependent force profile as expected. IW shows a very similar profile to the controls (dashed line) (colour figure online)

observation, we calculated the difference between the maximum angle of the movement in the direction of the perturbation and the angle of the endpoint (the angle subtended by the hook at the end of the trajectory). This measure of online correction was 11.4° for IW and $1.79^\circ (\pm 1.95^\circ)$ for the control, again a significant difference, $z = 4.89$, $p < 0.001$. Thus, IW showed a reduced drift of his endpoint in the direction of the force field and exhibited increased online corrections compared to controls.

However, Fig. 6a also reveals a strong asymmetry of the effect with respect to the direction of the force field. While the change in IW's anticlockwise endpoint (5.16°) was significantly different to the controls ($-22.0^\circ \pm 11.1^\circ$, $z = 2.45$, $p = 0.01$), the change in his clockwise endpoint (10.6°) did not differ significantly ($13.2^\circ \pm 6.37^\circ$). Similarly, the increase in online correction was mostly apparent in the anticlockwise force field ($z = -6.36$, $p < 0.01$). While they were also slightly higher than control values in the clockwise direction (5.76° vs. $0.59^\circ \pm 3.55^\circ$), this difference was not significant ($z = 1.46$, $p = 0.15$). One possible reason for this asymmetry is that IW used his left hand to perform the task, while nearly all the control participants used their right hand. Following this idea, both groups would show an increased drift towards flexion of the shoulder joint, possibly explained by stronger flexor than extensor muscles. While our one left-handed control participant did not show this effect, more left-handed participants would need to be tested to test this explanation further.

To test for the adaptation to the force fields themselves, we applied channel trials tilted to the participant's measured overall movement direction. The forces exerted during these channel trials (Fig. 6b) demonstrate that control subjects exhibited a force profile with a typical velocity-dependent profile as expected. IW's data showed a very similar pattern to the controls. Quantifying the force profiles as a mixture of position- and velocity-dependent force as above, we found that the velocity regression weights for the controls are significantly greater than zero (mean = 0.0564 , $t(6) = 12.8$, $p < 0.001$), and for IW, this regression weight was 0.0397 , which based on a z -score of -1.43 was not significantly different from the controls ($p = 0.152$). Similarly, the controls had a non-significant position regression weight (mean = 0.008 , $t(6) = 0.805$, $p = 0.452$), and IW's position regression weight (0.0485) was not significantly different to the controls ($Z = 1.54$, $p = 0.123$). Therefore, both the control group and IW adapted to the velocity force field without task-relevant feedback.

Discussion

The study of deafferented subjects has contributed greatly to our insight about the role of proprioception in motor

control and learning. However, such studies have relied on a small number of subjects with differing degrees of motor control and differing levels of deficit. Our study demonstrates that rather than relying on the fact that proprioception is generally impaired in these individuals, it is important to quantify the impairments of such subjects carefully for different tasks.

We have shown that the deafferented subject IW has lost most of his proprioceptive static position sense, as when the arm is moved passively to a new location, he was significantly impaired compared to the controls in localising his arm. This is in line with previous work which has shown that some deafferented subjects (GL) have inaccurate endpoints during reaching (Forget and Lamarre 1987) as well as an inability to sustain constant muscle contraction without vision (Rothwell et al. 1982), although IW has previously been shown to maintain a small force without feedback (Cole and Sedgwick 1992). The differences may reflect IW's long period of rehabilitation compared with the subject studied by Rothwell et al. and highlights the importance of differences between subjects with apparently similar conditions. While it has previously been shown that IW is able to actively perform simple repetitive movements without vision when position was not crucial (Cole and Sedgwick 1992), our task showed that IW was inaccurate at detecting the static position of his hand, i.e. when it had stopped after a passive movement to an unseen location.

The time elapsed after reaching could play a role in the accuracy of the localisation, since the static proprioceptive sense drifts with the time that a limb has been stationary (Paillard and Brouchon 1968). However, IW did not spend longer than our controls making his decision ($Z = -0.1708$, $p = 0.8644$), and therefore, this is unlikely to explain IW's impairment. We did not give subjects any feedback about hand position, once the static test had started, and therefore, subjects could have accumulated errors on hand position and become increasingly worse. However, we did not find that error increased with increasing number of trials and so this cannot account for differences in performance with this factor.

In contrast, in an active and dynamic proprioceptive test, where subjects made constrained reaches and had to discriminate perturbations to the right from the left, IW performed better than control participants. In controls, it has been suggested that the activation of muscles improves proprioception due to increased discharge from spindles (and Golgi tendon organs) during voluntary contraction (Gandevia et al. 1992; Laufer et al. 2001). It was recently shown that healthy controls are better at discriminating arm position when actively moving compared to when their arm is passively moved (Bhanpuri et al. 2013). Conversely, (Capaday et al. 2013) showed that when performing an active pointing movement, subjects were no more

accurate at localising their finger position than if their arm was passively moved. Similarly, our control participants did not perform better in the active compared to the static task and seemed to exhibit a form of force illusion, which impaired their performance during the active task. Subjects confused the direction in which their hand was pushed with the direction in which they pushed into the force channel, while IW did not show this effect.

The origin of IW's perception of perturbations under dynamic conditions is unclear. His perception of touch in the hand is poor, his von Frey monofilament threshold has previously been shown to be 200 mN compared with 6 mN for controls (Cole et al. 2006). Though we did not measure joint angulation during this task, most movement seemed to occur at the shoulder and elbow, with differing amounts of movement of each for different positions, especially for the static task. It is possible that IW has some remaining afferents from these joints and their muscles, undetectable from conventional testing of joint position sense, either by perception or matching between arms. However, the perturbations were more abrupt during the active task, and it is difficult to exclude afferent information being picked up through the neck, head, or possibly the inner ear.

One additional limitation is that the active and static perceptual tests of proprioception are different in difficulty and response (categorical versus continuous), and therefore, it is difficult to compare these tasks directly. Finally, although during the static task the arm was moved slowly to a new random position, we cannot rule out the possibility that subjects used dynamic information from the passive movement. Future work could employ the use of vibration during the passive movement to mask any proprioceptive information.

The observed dissociation allowed us to test the involvement of static and dynamic proprioception in force field learning. It has previously been shown that deafferented subjects as well as healthy controls can adapt to visual rotations (Bernier et al. 2006). More recently, it has been shown that deafferented patients can adapt to force fields with visual feedback (Sarlegna et al. 2010), and healthy controls can adapt to force field when proprioceptive and visual information are conflicting (Melendez-Calderon et al. 2011). Our results mirror these findings, such that IW was able to adapt to the force field when full vision was present (experiment 3) and when there was no task-relevant visual feedback (experiment 4). This use of visual information of the moving body part has been previously described as 'visual proprioception', and our results suggest that this remains preserved in IW. Furthermore, when analysing the forces produced in the channel trials, not only was the force field counteracted, but also the temporal shape of the force field (velocity- or position-dependent) was also reproduced. This indicates that IW not only learnt how to

reach the target in the presence of a force field, but did so in a way specific to the force field encountered. Given this result, we propose that the error-based learning required for force field adaptation uses active and dynamic rather than static proprioceptive information to improve performance.

Another learning modality which has recently been demonstrated for force field learning (Diedrichsen et al. 2010), spatial errors (Verstynen and Sabes 2011) and movement speed (Hammerbeck et al. 2014) has been referred to as use-dependent learning. This learning mechanism refers to the phenomenon that the next movement plan is updated to become more similar to the last experienced movement, if this movement was reasonably successful. When exposed to a force field during a task when the lateral deviation did not affect success, control subjects showed use-dependent learning in their endpoints, such that these participants shifted their desired endpoint in the direction of the perturbation. IW did not demonstrate this shift and maintained a central desired endpoint, as evidenced by the strong corrections at the end of the movement. One possibility is that IW pre-planned his movements in terms of a desired endpoint and increased his arm stiffness to achieve this position using equilibrium-point control (Polit and Bizzi 1978). The finding that IW produced adequate forces to resist a velocity-dependent force field in a force channel, however, argues against pure equilibrium-point control.

In the experiment, however, IW showed a little to no drift and large endpoint correction in the anticlockwise force field, but with nearly normal looking behaviour in the clockwise force field. While the reasons for this marked asymmetry are not fully clear, the explanation may lay in the fact that IW, who is left-handed, also performed the task with the left hand. An anticlockwise force field would have mostly loaded flexor muscles, which are stronger than extensor muscles, which would have allowed him better to resist the force field.

Our results suggest that the shift of the desired endpoint shown by controls may be caused by the proprioceptively sensed endpoint position of the hand becoming the desired or planned endpoint for the next movement. An alternative possibility is that the control group did not correct at the end of the movement, rather than shifting their endpoint. To test for this possibility, we put in channel trials at $\pm 8^\circ$ around the calculated preferred endpoint angle once subjects were force field-adapted. We found that subjects would correct towards their new endpoint if pushed away from it by a force channel (Diedrichsen et al. 2010). Therefore, this indicates that our control subjects actively shifted their endpoint rather than failed to correct.

In conclusion, we found that a chronically deafferented subject shows significantly worse static proprioception, and although not significant, slightly better mean dynamic proprioception than healthy, aged match controls. IW was also

able to adapt to force fields during a forward reach of the arm as well as healthy controls, but did not show a type of use-dependent learning. The questions of which receptors in which body parts underlay these results and the role of vision and motor learning remain unclear. These results suggest the adoption of caution when ascribing results from force field experiments to peripheral proprioception and to specific afferents or joints.

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