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Bimanual proprioceptive performance differs for right- and left-handed individuals

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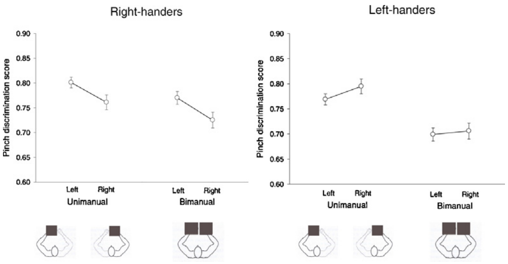
HIGHLIGHTS

- Proprioceptive asymmetry is mirrored for left- and right-handed individuals.
- Bimanual proprioceptive task performance is significantly worse than unimanual.
- The bimanual task performance reduction is significantly greater in left-handers.

GRAPHICAL ABSTRACT



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ABSTRACT

It has been proposed that asymmetry between the upper limbs in the utilization of proprioceptive feedback arises from functional differences in the roles of the preferred and non-preferred hands during bimanual tasks. The present study investigated unimanual and bimanual proprioceptive performance in right- and left-handed young adults with an active finger pinch movement discrimination task. With visual information removed, participants were required to make absolute judgments about the extent of pinch movements made to physical stops, either by one hand, or by both hands concurrently, with the sequence of presented movement extents varied randomly. Discrimination accuracy scores were derived from participants' responses using non-parametric signal detection analysis. Consistent with previous findings, a non-dominant hand/hemisphere superiority effect was observed, where the non-dominant hands of right- and left-handed individuals performed overall significantly better than their dominant hands. For all participants, bimanual movement discrimination scores were significantly lower than scores obtained in the unimanual task. However, the magnitude of the performance reduction, from the unimanual to the bimanual task, was significantly greater for left-handed individuals. The effect whereby bimanual proprioception was disproportionately affected in left-handed individuals could be due to enhanced neural communication between hemispheres in left-handed individuals leading to less distinctive separation of information obtained from the two hands in the cerebral cortex.

1. Introduction

Using movement detection [33], movement discrimination [19], movement or position matching [3,16] methods, upper limb proprioception has been extensively investigated at the fingers [26,48], wrists [1,2], elbows [3,13–15] and shoulders [4,25]. Recent studies have revealed a non-dominant arm superiority in proprioceptive

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Abbreviations: RH, right-handed; LH, left-handed.

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tasks [12–15]. The non-preferred arm/hemisphere specialization in the utilization of proprioceptive feedback has been attributed to functional differences between the roles of the preferred and non-preferred arms in bimanual tasks, where for both right- (RH) and left-handed (LH) individuals, the non-preferred limb positions and stabilizes, while the preferred limb executes controlled movements [15].

Many laboratory tasks, however, do not reflect a functional bimanual context, where the two hands perform two individual proprioceptive tasks concurrently. Rather, the proprioceptive performance of one limb/hemisphere system is generally assessed individually, although sometimes the contralateral arm is involved as the reference target [see 11 for a review]. In daily activities, however, bimanual movements are made more than twice as often as unimanual movements [30,40], and most bimanual movements involve different tasks, for example cutting a piece of paper while holding it with the other hand. In the conduct of bimanual movements, proprioceptive information from both hands must be processed simultaneously. At present, little is known about how bimanual concurrent proprioceptive information is processed in the brain, and whether the performance of each hand in bimanual proprioceptive tasks differs from the performance of the same hand in a unimanual proprioceptive task.

In general, when the two hands are required to perform different tasks concurrently, dual task interference appears and results in a decrement in performance of one or both hands [20,28,34]. If the dual task interference effect were evident in bimanual concurrent proprioceptive tasks, proprioceptive performance of one or both hands would be affected. However, different neural strategies could be used to process bimanual proprioceptive information, and then different results would be expected.

The hypothesis of functional differences between the roles of the two arms in bimanual tasks [15] predicts that upper limb asymmetries would be expected to remain evident in bimanual concurrent proprioceptive tasks, because a proprioceptive task favours the function of the non-dominant arm/hemisphere system – positioning – in bimanual tasks [15]. However, it has been argued that the hemisphere advantage observed in unimanual tasks does not extend to different bimanual tasks [20], suggesting that upper limb asymmetries may not be evident in a bimanual context.

The economy-in-energetics principle [36] predicts that bimanual proprioceptive performance would be lowered to the level of the lower performing hand. This observation has been reported in both lower and upper limb studies involving both injured and healthy individuals [41,42]. For example, a bimanual upper limb overhead movement discrimination study [41] found that when a single arm that performed well moved in conjunction with the other arm performing at a lower level, the result was lowered bimanual movement discrimination performance. Similarly, the sensory selection notion suggests that the brain tends to be biased towards one sensory input and will ignore or curtail other sources of related information [37]. For RH individuals, sensory selection or sensory gating has been found to be biased towards the right/dominant side [37]. Taken together, this evidence suggests that, when bimanual proprioceptive tasks are carried out concurrently, the consequence would either be to lower the normally superior performance of the non-dominant hand to the level of the dominant hand to save energy costs, or bias towards proprioceptive input from the dominant hand and ignore or curtail proprioceptive information from the non-dominant hand to save attention costs. Consequently, the non-dominant arm superiority observed in unimanual proprioceptive tasks would not be evident, i.e., there would be no upper limb proprioceptive asymmetry in bimanual proprioceptive tasks.

Recent studies have suggested that upper limb proprioceptive asymmetries are dependent on handedness [3,15] and gender [3]. Goble and colleagues [14,15] found these asymmetries to be mirrored between LH and RH individuals, while this mirror asymmetry was observed only in males in a study by Adamo et al. [3]. Other sensorimotor studies have found that LH individuals are simply less lateralized [17,29], or even identical to their RH counterparts [7]. What is unknown is the extent to which LH individuals might show different patterns than those predicted for RH individuals in bimanual concurrent proprioceptive tasks.

It has been argued that, in testing proprioceptive acuity, it is important that the tests maximize the similarity between the laboratory test and real life function, i.e., maximize ecological validity [10], so that individuals can integrate all normally available proprioceptive information from different receptors, such as cutaneous receptors, joint receptors and muscle spindles [9,46]. Accordingly, in the current study we employed an active finger movement extent discrimination apparatus (AFMEDA) that screens the target from vision, so that absolute judgments on finger movements must be based on proprioception [19]. The AFMEDA design is based on the principle of replicating functional movement [6,43], that is, active rather than passive movement, at a normal speed, without physical constraint of other body segments such as is involved in methods that use passive finger movement [e.g., 45], isolate a single finger joint [e.g., 39] or strap the testing finger [e.g., 48]. In addition, the nature of the AFMEDA task ensures that information about both finger movement extent and end position is available on every trial, and this combination allows for better performance than that which is seen with extent information alone [21]. By testing thumb-index finger pinch movement discrimination of the two hands between two groups specified for handedness, two genders and two conditions (unimanual and bimanual), we sought to compare proprioceptive performance differences.

2. Materials and methods

2.1. Participants

Ten RH individuals (5 males and 5 females, mean age = 21.6 years, SD ± 1.5) and ten LH individuals (6 males and 4 females, mean age = 21.1 years, SD ± 1.7) were recruited by an advertisement placed on a campus notice board. Participants demonstrated strong right or left hand preference, as evidenced by laterality quotients calculated from a ten-item version of the Edinburgh Handedness Inventory [27]. The scores for RH participants were mean ± SD laterality quotient, +83.0 ± 14.6, range from +65 to +100; and the scores for LH participants were mean ± SD laterality quotient, −78.0 ± 12.1, range from −65 to −100. Prior to inclusion, all participants completed a health questionnaire to exclude the presence of hand injuries within the past 6 months or a diagnosis of chronic diseases (e.g., multiple sclerosis, stroke, Parkinson's disease, rheumatoid arthritis, type 2 diabetes) [19].

The project was approved by the University of Canberra Committee for Ethics in Human Research (CEHR 10-110) and before commencing each participant provided informed consent.

2.2. Apparatus

The AFMEDA was used to generate the stimuli for the finger pinch movement discrimination task. The apparatus (Fig. 1) consists of two symmetrical coaxial aluminium alloy tubes with thimbles embedded at one end to stabilize the index finger and thumb and thereby enable participants to freely execute a pinching movement of the thumb and index finger. There were five possible pinch distances generated by five adjustable metal stops, which were screw heads of different diameters tapped into the central wheel, such that the smaller the screw head the greater the

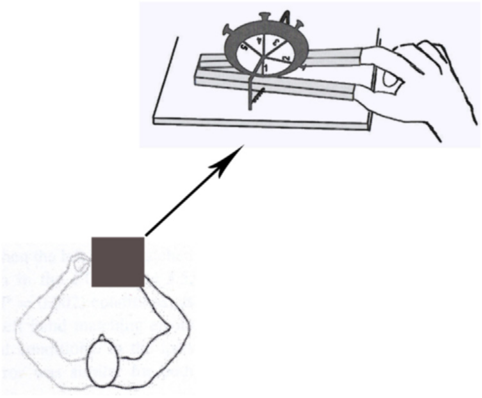

Fig. 1. Depiction of setup of the unimanual active finger pinch movement discrimination test. To examine bimanual execution of pinch discrimination, the apparatus was duplicated to allow simultaneous application by both hands.

finger pinch movement required before contact. The linear pinch movement displacement distances thus generated were: position 1 = 15.5 mm, position 2 = 13.0 mm, position 3 = 10.5 mm, position 4 = 8.0 mm and position 5 = 5.5 mm. The extent of each movement was obtained by measuring the distance from the end of the tube in the fixed start position to where the tube contacted the rim of the metal stop at the end position. To examine bimanual execution of pinch discrimination in the present study, the apparatus was duplicated to allow simultaneous application by both hands.

2.3. Procedure

While sitting comfortably, with thumb and index finger in place, the apparatus and testing hand(s) were covered to prevent the use of visual information. Participants were instructed to make an active pinch movement that moved the tubes from the fixed start position closer to the midline until contact was made by the medial rims of the tubes, and to return the tubes to the start position, with assistance from a light spring attached to each tube.

During the familiarization session before data collection, each participant was informed that they would experience the five pinch displacement distances in order, from the largest (position 1) to the smallest (position 5), three times: 15 trials in all. Thus participants experienced the positions 1, 2, 3, 4 and 5 in sequence, for 3 rounds in total. After the 15-trial familiarization, participants then undertook 50-trials of testing, in which all five positions were presented 10 times, in a random order. During testing, participants were asked to make a judgement as to the position number (1, 2, 3, 4 or 5) of each pinch movement as soon as they returned the tubes to the start position, without feedback being given as to the correctness to the judgement they made for each trial. That is, the participants used their memory of the 5 pinch positions from the familiarization trials to enable them to evaluate the current stimulus and thus make a numerical judgement about each stimulus as it was presented. This task was thus a single stimulus, or absolute judgement task, wherein a single stimulus was presented and single response was made on each trial. A complete test, including 15 familiarization trials and 50 test trials, took approximately 10 min.

The order of the two testing conditions, unimanual and bimanual pinch discrimination, was randomized. For the unimanual pinch discrimination task, the order of testing the right or left hand was randomized, and for the bimanual concurrent pinch discrimination task, where the pinch distance varied randomly for each hand, the required order of reporting judgement for the left or right hand was also randomized.

2.4. Data analysis

For each test, the raw data were entered into a 5×5 matrix representing the frequency with which each response was made for each stimulus. Non-parametric signal detection analysis was applied to produce pair-wise receiver operating characteristic (ROC) curves, i.e., comparing responses to distances 1–2, 2–3, 3–4 and 4–5 [18,22,24]. Thereafter, the mean pair-wise area under the curve (AUC) was calculated using SPSS software V.18 to give each participant a single pinch movement discrimination score. The AUC was derived from the ROC curve through non-parametric signal detection analysis, and provided an unbiased estimate of the ability of individual to discriminate between the five different stimuli [38]. AUC values range from 0.5, equivalent to chance responding, to 1.0, representing perfect ability to discriminate between the 5 different movement extents.

To test whether the Goble et al. [14,15] non-dominant arm/hemisphere hypothesis about superiority in unimanual proprioceptive tasks was also observed in bimanual proprioceptive tasks, a $2 \times 2 \times 2 \times 2$ factorial repeated measures ANOVA was conducted, with two group factors, Handedness (RH, LH) and Gender (male, female), and two repeated measures factors, Hand (right, left) and Task Type (unimanual, bimanual). To determine if there were any between-group or between-condition differences, an ANOVA with repeated measures was employed.

3. Results

The mean AUC values representing pinch movement discrimination for groups and conditions are shown in Fig. 2. There was no overall effect of Handedness ($F_{1,16} = 2.1$, $p = 0.17$, partial $\eta^2 = 0.12$), of Hand tested ($F_{1,16} = 2.7$, $p = 0.12$, partial $\eta^2 = 0.14$), or of Gender ($F_{1,16} = 0.02$, $p = 0.89$, partial $\eta^2 = 0.001$) on pinch movement discrimination scores. However, an overall Task Type effect was observed, wherein the unimanual movement discrimination task was performed significantly better than the bimanual movement discrimination task ($F_{1,16} = 47.5$, $p < 0.001$, partial $\eta^2 = 0.75$). Further, a significant interaction effect between Task Type and Handedness was obtained, with the unimanual-to-bimanual task decrement being significantly greater for LH individuals ($F_{1,16} = 7.8$, $p = 0.013$, partial $\eta^2 = 0.33$). For LH individuals, bimanual movement discrimination scores were on average 10% lower than their scores on the unimanual task, whereas bimanual scores were 4% lower for RH individuals. The effects of Task Type were not significantly different whether the Hand tested was left or right ($F_{1,16} = 1.1$, $p = 0.30$, partial $\eta^2 = 0.67$).

The non-dominant hand/hemisphere superiority effect was observed as a significant interaction between Handedness and Hand tested, where the non-dominant hands of RH and LH individuals performed overall significantly better than their dominant hands ($F_{1,16} = 14.4$, $p = 0.002$, partial $\eta^2 = 0.47$). The three-way interaction, Handedness × Hand × Task Type, was not significant ($F_{1,16} = 0.29$, $p = 0.60$, partial $\eta^2 = 0.02$), indicating that the non-dominant arm superiority was observed irrespective of the type of task, unimanual or bimanual.

No other 2-, 3- or 4-way interaction involving the repeated measures factors Hand and Task Type was significant (all $p > 0.26$), and no interaction involving Gender was significant (all $p > 0.16$).

4. Discussion

The current study compared performance between unimanual and bimanual proprioceptive tasks by testing active finger pinch movement discriminative ability in both RH and LH individuals,

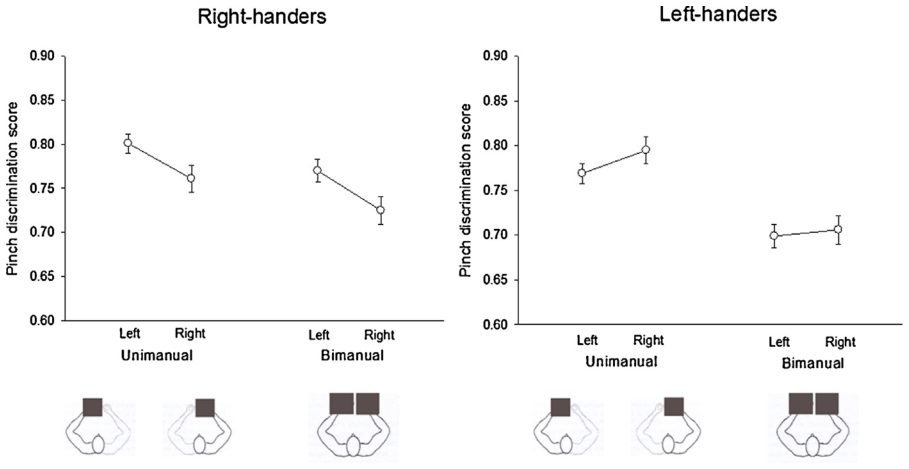

Fig. 2. Mean pinch discrimination scores for the left and right hands of the RH and LH groups when performing the unimanual or bimanual versions of the task. First report of judgement in the bimanual condition was randomly left or right. The icons show the hand being tested with the screens in place. The error bars represent one standard error.

males and females. Two main findings emerged from the data analysis.

The first finding showed that the non-dominant hand/hemisphere superiority effect was obtained as a significant interaction between Handedness and Hand tested, where the non-dominant hands of RH and LH individuals performed overall significantly better than their dominant hands. This is consistent with previous research work of sensorimotor abilities [15,44], suggesting that right hand/hemisphere dominance for pinch movement discrimination in LH individuals is the "mirror image" of their RH counterparts. In addition, no significant effect was observed in the Handedness × Hand × Task type three-way interaction, indicating that the non-dominant arm/hemisphere superiority was irrespective as to whether the task was performed unimanually or bimanually. This finding contradicts the prediction that sensory selection or sensory gating would be biased towards the dominant side when individuals are required to perform bimanual pinch movement discrimination tasks concurrently [37], and that the hemisphere advantage observed in unimanual tasks would not extend to different bimanual tasks [20]. Rather, the results here support the Goble et al. hypothesis of functional differences between the preferred and non-preferred limbs during bilateral tasks [15]. In daily functional activities, the non-preferred hand is usually used to statically pinch/grasp objects in a specific position for the preferred upper limb to manipulate, for example, when cutting a piece of paper or removing a bottle lid. It is hypothesized that, over time, repetition could lead to use-dependent neuroplastic alterations of the hemisphere contralateral to each limb [15,18]. Thus, fingers in non-preferred hand are more likely to receive more "positioning" practice, resulting in more accurate discrimination of movement extent, as observed here in both RH and LH participants. This finding is also consistent with Sainburg's proposition that the non-preferred arm/hemisphere system is specialized for static limb position control, whereas the preferred arm/hemisphere system is specialized for dynamic limb trajectory control [31,32].

Another main finding of the present study was that although the bimanual task decrement in movement discrimination performance occurred in both hands for both RH and LH individuals, the degree of decrement differed between RH and LH individuals. Data analysis showed a significant Task Type main effect, where the bimanual movement discrimination task was performed significantly more poorly than the unimanual movement discrimination task. This finding is not unexpected, and is in line with results from previous bimanual concurrent motor task studies [20,28,34]. However, the significant interaction effect between Task Type and Handedness showed that magnitude of the performance reduction from unimanual to bimanual task was significantly greater for left-handed individuals. For LH individuals, bimanual movement discrimination scores were on average 10% lower than their unimanual task scores, an amount which is 2.5 times greater than that for RH individuals.

The effect that bimanual proprioception was disproportionately affected in left-handers could be due to the enhanced inter-hemispheric communication that is thought to be evident in LH individuals leading to less distinctive separation of information obtained from the two hands in the cerebral cortex. The corpus callosum is considered the primary structure for information transfer between the two hemispheres [5,35]. Research evidence has shown LH individuals to have a larger corpus callosum [47], and to display a faster inter-hemisphere transfer time [23] and a higher inter-hemisphere transfer efficiency [8] than their RH counterparts. It is possible that, for proprioceptive information arising from making bimanual movements, LH individuals may transfer this information between hemispheres more quickly. The faster communication between the two hemispheres for LH individuals therefore has the potential to temporally overwhelm the other information that is currently being held in the primary receiving hemisphere. As a consequence, LH individuals showed a less distinct cortical representation of the two hands than RH individuals. This could lead to a greater confusability between the two hands, in terms of what proprioceptive information comes from which hand, in the brains of LH individuals, and could account for the relatively greater decrement from the unimanual to the bimanual task that was found for LH individuals.

In conclusion, the present study extends the current understanding of the behavioural differences between RH and LH individuals in proprioceptive tasks. The results here replicate findings from previous unimanual sensorimotor studies that have reported reversed asymmetries between RH and LH individuals [15,44], and extend the notion observed in unimanual proprioceptive tasks, that the non-dominant arm/hemisphere is specialized in the utilization of proprioceptive feedback [14], to a bimanual proprioceptive testing condition. In addition, the novel finding that bimanual proprioception was disproportionately affected in left-handed individuals could be attributed to differences in hemispheric interactions between RH and LH individuals, where enhanced neural communication between hemispheres in LH individuals may result in a less distinctive separation, in the cerebral cortex, of information obtained from the two hands.

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