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RESEARCH ARTICLE

Compromised encoding of proprioceptively determined joint angles in older adults: the role of working memory and attentional load

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Abstract Perceiving the positions and movements of one's body segments (i.e., proprioception) is critical for movement control. However, this ability declines with older age as has been demonstrated by joint angle matching paradigms in the absence of vision. The aim of the present study was to explore the extent to which reduced working memory and attentional load influence older adult proprioceptive matching performance. Older adults with relatively HIGH versus LOW working memory ability as determined by backward digit span and healthy younger adults, performed memory-based elbow position matching with and without attentional load (i.e., counting by 3 s) during target position encoding. Even without attentional load, older adults with LOW digit spans (i.e., 4 digits or less) had larger matching errors than younger adults. Further, LOW older adults made significantly greater errors when attentional loads were present during proprioceptive target encoding as compared to both younger and older adults with HIGH digit span scores (i.e., 5 digits or greater). These results extend previous position matching results that suggested greater errors in older adults were due to degraded input signals from peripheral mechanoreceptors. Specifically, the present work highlights the role cognitive factors play in the assessment of older adult proprioceptive acuity using memory-based matching paradigms. Older adults with LOW working memory appear prone to compromised proprioceptive encoding, especially when secondary cognitive tasks must be concurrently executed. This may ultimately result in poorer performance on various activities of daily living.

Keywords Proprioception · Working memory · Position sense · Aging · Attentional loading

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Introduction

Proprioception encompasses the perception of one's body segment positions and movements in space. Using assessments of joint angle matching ability without vision, older adults have been shown to have decreased proprioceptive sensibility compared to younger adults (for reviews see Goble et al. 2009a, b; Goble 2010). In such studies, increased matching errors for older individuals have typically been ascribed to degradation of the peripheral mechanoreceptors in the muscle, skin and joints with older age (Shaffer and Harrison 2007). However, it should be noted that joint angle matching tasks inherently require cognitive processes, particularly when matching tasks involve the reproduction of memorized joint angles (Adamo et al. 2007, 2009; Petrella et al. 1997; Hurley et al. 1998; Westlake et al. 2007). In this case, it seems plausible that the more prevalent decline in working memory (WM) associated with older age (e.g., Bopp and Verhaeghen 2005) might predispose older adults to poorer performance on memory-based joint position matching tasks.

Another cognitive process that may contribute to declines in proprioceptive matching performance in older adults is attentional load. Indirect support for this hypothesis can be garnered from dual-task studies involving the maintenance of upright stance—a task that substantively relies on proprioceptive information (Lord et al. 1991). When performing secondary cognitive tasks during standing, such as counting or numerical recall, older adults experience compromised balance, particularly when cognitive performance is prioritized over standing (Brown et al. 1999; Doumas et al. 2008, 2009; Maylor and Wing 1996). These results suggest that, in dual-task situations, reduced resources can contribute to decline in sensorimotor performance with age (Woollacott and Shumway-Cook 2002).

The objective of the present study was to determine whether WM and attentional load influence assessment of upper limb proprioceptive ability in older adults when a memory-based joint angle matching paradigm is utilized. Older individuals with differing working memory and executive control abilities, as measured by a backward digit span test (Wechsler 1981), were compared on an established ipsilateral remembered elbow joint angle matching task (Adamo et al. 2007; Goble and Brown 2007, 2008; Goble et al. 2010). The matching task was performed with and without a secondary counting task during the target encoding phase, which served as an attentional load. Healthy young adults were also tested to provide a means of comparison between young and older adults. Overall, it was hypothesized that matching errors would be increased for older adults with lower versus higher backward digit spans, especially when attentional load was present during target encoding. This result would demonstrate for the first time the important role working memory and/or attentional load can play in the assessment of proprioceptive ability via memory-based joint position matching.

Methods

Participants

Eleven younger (mean age = 21.0, range = 18.6–22.1 years) and 16 older (mean age = 75.9, range 65.1–87.8 years) right-handed (Oldfield 1971) individuals from the greater Ann Arbor, Michigan community participated in the study. Although previous work suggests that no differences exist between males and females on tests of proprioceptive matching (Goble et al. 2006), only women were tested to eliminate any sex-related variance. Adequate cognitive state was verified using the Mini-Mental State Examination (MMSE; Folstein et al. 1975) at the time of testing with a minimum score of 27/30 required. All participants reported being in good general health at the time of testing with no known neurological, psychiatric or muscular disorder. Some older adults used medication to regulate body homeostatic properties such as blood pressure, but no motor or cognitive side effects were noted.

Older adults were separated into two equal ($n = 8$) groups based on backward digit span ability. Backward digit span was chosen as it is thought require both working memory and attention-related executive control components of cognitive function (Bopp and Verhaeghen 2005; Gregoire and Van der Linden 1997), which seemed likely to influence proprioceptive performance on memory-based joint repositioning tasks. Digit spans were quantified according to the methods of Wechsler (1981). Briefly, series' of digits were read aloud by the experimenter at a rate of approximately one digit per second. Participants then repeated each series in reverse order. The first series of digits was two numbers long and each successive series was one digit longer. Two trials were given for each length of digit-series and a score was determined equal to the largest series repeated without error.

Older individuals with digit spans of 5 or greater were placed in the HIGH group ($n = 8$, mean age = 75.6 years) and those with digit spans of 4 or less were placed in the LOW group ($n = 8$, mean age = 76.1 years). The HIGH older adults, represented approximately the 40th percentile of performance for their age group, while the LOW group fell in the bottom 60th percentile (Iverson and Tulsky 2003). Younger participants in this study all had spans of at least 5 digits (i.e., were comparable to the HIGH older adults). Since spans of 4 digits or less are atypical in young adults (Iverson and Tulsky 2003), a young group comparable to the LOW older adult group was not recruited.

Proprioceptive matching paradigm

The proprioceptive matching setup utilized in this study has been described elsewhere in detail (Goble et al. 2005; Goble and Brown 2007). In short, blindfolded participants were seated with their right forearm placed on an aluminum manipulandum designed to record elbow angle in the horizontal plane. Starting shoulder (80° abduction, 15° flexion), elbow (100° extension), and wrist (neutral) angles were standardized across subjects. A handle on the distal end of the manipulandum was used to rotate the forearm about the elbow such that the experimenter did not make physical contact with participants.

In the first, (i.e., *no load*) proprioceptive matching condition, five trials were conducted consisting of two phases. In the first phase, *target encoding*, the experimenter extended the participant's elbow 20°, 30°, or 40° from the start position. This proprioceptive target was maintained approximately 2 s while the participant encoded it in memory. The arm was then returned to the start position and, following a 2 s delay, the *target matching* phase commenced. Here, the experimenter verbally cued the participant to "match" the encoded target position. Participants then had unlimited time to replicate the previously experienced target location via an elbow extension movement. Once matching was completed, the experimenter replaced the elbow back at its original starting angle in preparation for the next trial.

In the second proprioceptive matching condition (i.e., *attentional load*), a similar procedure to that described for the no load condition was utilized. However, in this case, participants were required to perform a secondary task during the target encoding phase that involved counting upwards by three from a random number between 1 and 100. Participants were instructed to prioritize the counting task over attending to elbow joint position. To ensure participants were engaged in this secondary task, arm displacement to the target did not commence until 3 digits of the sequence were completed. Counting occurred at a rate of approximately 1 number per second.

Following target encoding, the starting elbow angle was restored and participants ceased counting. The target matching phase was then completed as described for the no load condition. Five trials were undertaken. Overall, the order of presentation for attentional load versus no load conditions was blocked and balanced within and across the various age and digit span ability (i.e., HIGH versus LOW) groups. Participants were given 5–10 min of practice to ensure familiarity with the procedures and equipment. During practice, participants were first presented with the no load matching task and then practice of the loaded matching task occurred until the participant demonstrated the ability to maintain the proper timing for counting on at least 3 consecutive trials. Older adults typically took longer than young adults to learn the matching task with cognitive load, although this was not always the case. There were no observable differences between the HIGH and LOW older adult groups in how long it took to learn the procedure and no feedback was given to participants regarding the accuracy of their proprioceptive matches to ensure learning of the angles to be matched did not occur.

Data analysis

Proprioceptive ability was determined via a total error measure, which was determined according to the method of Henry (1974). This error type is an idealized combination of bias (i.e., constant error) and variability (i.e., variable error). Additionally, two kinematic measures of the matching movements made were quantified. First, movement duration was defined as the time difference between movement offset and onset with these time points being determined via an algorithm based on changes in velocity that were 2 SD from the mean baseline (i.e., no forearm displacement) signal. Second, average velocity was taken equal to the final elbow angle divided by movement duration.

Independent samples *t* tests were first conducted to assess any group (young, older HIGH, older LOW) differences on various cognitive and demographic variables, as well as the accuracy of counting by 3 s in the dual-task situation. Next, dependent variables were subjected to a 2×3 multiple ANOVA with conditions GROUP (younger, older HIGH, older LOW) as a between subjects factor, and LOAD (load, no load) having repeated measures. Statistical significance was considered at alpha <0.05 and Tukey's honestly significant difference (HSD) test was used post hoc to decompose interactions. Partial eta squared served as a measure of effect size where appropriate.

Results

Although a significant difference was seen in the backward digit spans of the HIGH (mean = 5.5 digits) and LOW (mean = 3.6 digits) older adults, $t(7) = 5.4$, $P = 0.001$, these two groups did not differ in terms of age (mean age HIGH = 75.6 years; mean age LOW = 76.1 years; $t(7) = 0.1$, $P = 0.89$), handedness score (mean laterality index HIGH = 92.5; mean laterality index LOW = 93.7; $t(7) = 0.2$, $P = 0.82$) or MMSE (mean HIGH = 29.3; mean LOW 29.1; $t(7) = -0.2$, $P = 0.83$). Further, with respect to the younger adults tested, there was only a significant difference in backward digit span when comparing their results to LOW ($t(7) = 4.0$, $P < 0.01$), but not HIGH ($t(7) = 0.5$, $P = 0.61$), older adults. Counting errors in the dual-task condition were rare, occurring in only 2 trials across all subjects (1 young, 1 LOW) and accounting for <2% of data collected. Not surprisingly, this did not result in any group differences ($P > 0.05$).

In Fig. 1, proprioceptive matching accuracy (i.e., total error) is displayed for younger, older HIGH and older LOW groups in each loading condition. These data were characterized by a significant GROUP × LOAD interaction, $F(2,24) = 6.8$, $P < 0.01$, partial eta squared = 0.36, where matches made in the loaded condition by older individuals with LOW digit spans showed greater total error (i.e., less accuracy) than any other condition tested, Tukey HSD, $P < 0.05$. An additional, significant difference was seen during post hoc testing between the young and older LOW group in the no load condition, Tukey HSD, $P < 0.05$. Specifically, younger adults had smaller total errors than LOW older adults.

Matching movement kinematics (i.e., average movement velocity and duration) were similar for all three groups tested regardless of the loading condition. Overall, matching movements appeared to be made in a slow and controlled manner. The mean average matching movement velocity was approximately 16.9 deg/s with a mean duration of approximately 2.2 s.

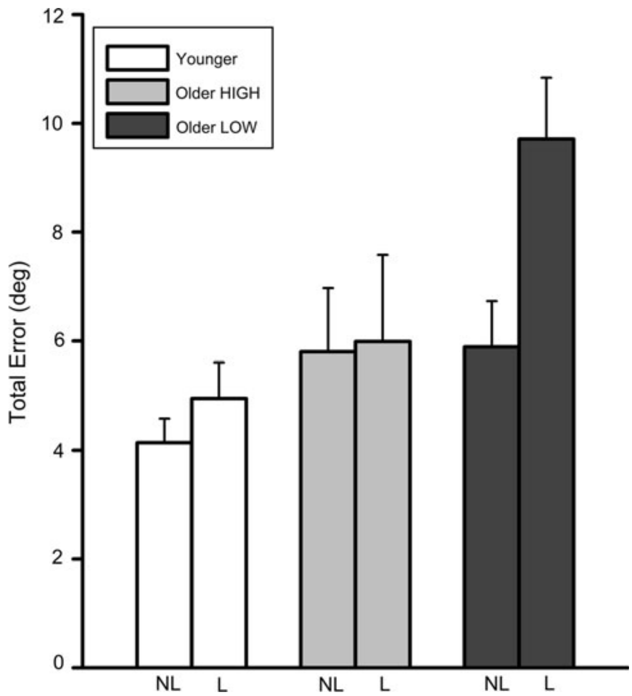

Fig. 1 Mean (±SE) total errors associated with proprioceptive matching in the no load (NL) and load (L) conditions

Discussion

Declines in proprioceptive sensibility are often measured via proprioceptive matching tasks and are known to have a significant relationship with the sensorimotor well-being of older adults (Goble et al. 2009a, b; Hurley et al. 1998). The present study sought to determine whether WM and/or attentional loading might influence performance on assessments of proprioceptive acuity involving the memory-based matching of previously experienced joint angles by older adults. It was shown that older individuals with poorer working memory and executive control (i.e., LOW digit span group) recalled elbow angles with greater error than young adults, regardless of attentional loading condition. Further, LOW older adults made significantly greater errors than both young and HIGH older adults when target encoding was disrupted by attentional load (i.e., counting). These findings were not related to the kinematics of the matching (i.e., duration or velocity) and, therefore, suggest cognitive factors play a role in the assessment of proprioceptive ability using joint matching paradigms.

The idea that proprioceptive matching paradigms inherently involve cognition, and is not a simple reflection of proprioceptive signals from mechanoreceptors in the periphery, has rarely been noted in the literature (c.f. Adamo et al. 2007; Goble and Brown 2007, 2010; Goble et al. in press). As such, this was the first known study to directly test the role WM and attentional loading have on memory-based matching performance in adults with lower cognitive ability in these domains. The overall reduction in matching accuracy seen for older adults with LOW backward digit span ability (i.e., poorer WM and executive control) strongly suggests that memory for proprioceptive target information shares a common neural substrate with the ability to encode, manipulate and recall digits. Further, the significant increase in matching error for the LOW older group during the attentional load condition parallels previous work showing age-related differences in dual-task performance, including tasks known to rely on proprioception such as standing (Brown et al. 1999; Doumas et al. 2008, 2009; Maylor and Wing 1996) and walking (Li et al. 2001; Lindenberger et al. 2000). Based on these studies, it has been purported that allocation of attentional resources toward a task can lead to compromised sensorimotor performance due to a limitation in resources available for concurrently coping with both tasks (Woollacott and Shumway-Cook 2002). This proposition fits well with the present, memory-based matching results, where it seems likely that diverted attention toward the prioritized counting task exacerbated the poorer memory abilities of LOW older adults.

In the present study, an attentionally demanding counting task was incorporated as the secondary task, rather than a task involving working memory. This approach was utilized as, first, it is difficult to find a "pure" memory task that would not also involve additional attentional and/or executive function components. In this case, any increase in matching error in the dual-task situation would be difficult to ascribe to attention versus memory deficits or the combination of both. Second, the counting had the advantage of assessing both the effects of reduced digit span on proprioceptive memory by itself (i.e., the no load condition), as well as the influence of attention on matching performance (i.e., the load condition). This allows for a more streamlined interpretation of results showing that backward digit span influenced performance in both load and no load conditions, thus, implying that there is a role for both memory and attention in the assessment of proprioception via a memory-based matching task.

Several limitations of the present study bear noting, as they are may stimulate further exploration in future experiments. First, a memory-based matching task was utilized whereby participants matched passively determined targets through active replication movements. This task type was selected based on its prevalence in current aging research (see for review Goble et al. 2009a, b), and due to practical advantages over, for example, active target selection paradigms. Specifically, the present procedure allowed for controlling known effects of differing target amplitudes across subjects (Goble et al. 2006, 2009a, b; Goble and Brown 2008, 2009) and eliminating the availability of an efferent copy of the motor command as a source of information to guide matching (Goble and Brown 2007). Regardless, future studies involving the use of self-selected targets and/or proprioceptive tasks that more closely mimic activities of daily living are warranted. To this extent, promising recent work by Cressman et al. (2010) has elucidated age-related changes in the upper limb proprioceptive acuity of older adults involving the estimation of hand position in a two-dimensional plane.

A second potential limitation of the present study was that younger individuals tested were only matched to the HIGH older adult group in terms of backward digit span performance. Adding a group of younger adults comparable to the LOW older group might have revealed whether the observed memory by attentional load interaction was specific to older individuals. To this point, it is important to note that digit spans of the magnitude seen for LOW older adults in this study (i.e., 4 digits or less) are atypical in young adults and may reflect pathologies such as schizophrenia (Brebon et al. 2009) or autism spectrum disorder (Poirier et al. 2011). In contrast, nearly 60% of older adults fall within the LOW range of backward digit spans utilized in this study (Iverson and Tulsky 2003). As such, it is logical to conclude the present results hold particular relevance for older versus younger adults.

Lastly, given the relatively large age range in the older adults tested, there is potential for selection bias, such that the oldest individuals tested may have been less representative of their age-matched peers than the younger older adults tested. In this case, however, it would seem logical to assume that use of such individuals would serve to underestimate the magnitude of the present findings, as deficits are likely to be more exaggerated in the general population at large. In future work, it would be of interest to further address this possibility through a more extensive battery of cognitive tests and compare the results to standardized norms. This does not, of course, discount the importance of the present relationship described between proprioceptive acuity and backward digit span ability. Rather, it raises the question as to whether other cognitive factors such as verbal ability, episodic memory or cognitive speed might also influence performance on tests of proprioceptive matching ability.

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