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ORIGINAL ARTICLE

Posture biofeedback increases cognitive load

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Abstract
Attention may be important for actively maintaining posture during computer tasks, resulting in a dual-task tradeoff, where maintaining posture through extrinsic feedback imposes cognitive load. Mindfulness may make intrinsic postural feedback (which imposes less cognitive load) more available. Therefore, we hypothesized that the use of biofeedback would improve posture and negatively impact game performance; additionally, higher levels of mindfulness would be associated with lower game performance costs in the biofeedback condition. Healthy young adult participants played a challenging computer game for 10 min with and without neck length biofeedback, in a counterbalanced repeated-measures design. For each condition, we assessed posture using neck shrinkage (percentage of best), and task performance (computer game score). Neck length was better retained and game performance was worse with biofeedback than without, consistent with the hypothesis that posture biofeedback imposed a cognitive load. In addition, participants with the most neck shrinkage suffered the greatest performance decrements from using biofeedback, and neck length retention during the task without biofeedback was associated with lower self-reported daily neck pain and higher self-reported mindfulness. Thus, those with the greatest need for postural feedback suffer the greatest performance decrements from extrinsic feedback. The results are consistent with the idea that mindfulness enables people to use intrinsic feedback to maintain posture without imposing a dual-task cost.

Introduction

In cognitive psychology, attention is considered a finite resource, and tasks that draw on this resource are said to incur cognitive load. Cognitive load is typically assessed in dual-task designs in which participants perform two tasks, singly and concurrently. If both tasks require attention, performing them concurrently results in a performance decrement relative to single-task performance. This decrement, referred to as a dual-task cost, increases with cognitive load resulting in an attentional tradeoff, where attention given to tasks is prioritized based on the perceived importance of each task.

Attention may be important for actively maintaining posture during computer tasks. Although balance is known to require attention (Woollacott & Shumway-Cook, 2002), maintaining postural alignment has not previously been considered a task which incurs a cognitive load. We recently demonstrated that neutral posture is not maintained before anticipated movement, especially when the anticipated movement is difficult (Baer et al., 2019). This finding suggests that the task of maintaining posture might be ignored in the presence of increased cognitive load. Therefore, investigations of interventions to improve posture need to address the possibility of concomitant performance decrements due to increased cognitive load.

Biofeedback devices are a relatively new intervention that may be used to reduce neck pain during computer work (Simpson et al., 2019). Neck pain is a common musculoskeletal issue across multiple populations and age groups (Haldeman et al., 2010), often attributed to deviations from neutral posture during seated work (Ariëns et al., 2001; OSHA, 2020). Numerous proprietary biofeedback devices available on the market promise to improve posture by delivering a simple tactile or auditory cue when a person slouches or bends forward (Ailneni et al., 2019; Hwang, 2019). Though this idea is enticing, it relies on underlying concepts that

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have not yet been adequately investigated. For instance, there may be cognitive costs associated with biofeedback-based correction of posture that have not yet been considered.

Cognitive load in a dual-task paradigm occurs when cognitive resources overlap between two tasks that are performed simultaneously. Both maintaining postural alignment and performing complex computer tasks may rely on visuomotor performance and prospective memory. Many computer tasks and games rely heavily on visuomotor performance for fast response times and coordination of fine motor movements (Li et al., 2016); and on prospective memory to manage sequential tasks and complex decision-making (Martin & Schumann-Hengsteler, 2001).

To our knowledge, our previous study is the only one which has investigated the cognitive demands of postural alignment (Baer et al., 2019). Postural alignment is inherently a visuospatial (or at least spatial) task, so it might be expected to compete for that cognitive resource. In addition, attempting to change habitual postural alignment is likely to draw on prospective memory. When a person makes a plan to act against existing habits, interference is created by a conflict between well-learned responses and the intention to incorporate new prospective memory cues (Pink & Dodson, 2013). Postural alignment is probably a very well-learned habit, so intending to change postural alignment may incur cognitive load.

The opposite of doing things habitually is doing them mindfully. Mindfulness is defined as the ability to maintain attention on the present and on intended tasks through self-regulation (Bishop et al., 2004). Mindfulness interventions have been shown to improve many facets of attention management (Jha et al., 2007; Sanger & Dorjee, 2015) and reduce cognitive load in decision-making (Reber, 2014). Thus, if attending to posture increases cognitive load, then mindfulness might ameliorate that load by increasing the total pool of attentional resources available or by lowering the amount of attention needed to notice small changes such as those associated with posture. We previously demonstrated that individuals who score higher on a self-report of mindfulness display less forward head posture when anticipating a movement than individuals who report lower mindfulness (Baer et al., 2019). This suggests that mindfulness may facilitate the awareness of deviations from neutral posture, leading to improved ability to maintain posture. In the context of maintaining posture, mindfulness may, thus, facilitate the use of *intrinsic feedback* (Patchan & Puranik, 2016).

Posture is most often assessed based on external measurement of body angles. However, due to substantial variation in neutral postural angles among individuals (Silva et al., 2009), there is no validated way to objectively define "optimal" neutral posture. Moreover, external angular measurements are not valid indicators of internal spinal alignment (Correia et al., 2021; Vasavada et al., 2015). Another way to assess posture may be to focus on *neck shrinkage*, which can be represented objectively by relative decreases in neck length from neutral. Spinal shrinkage is generally measured in terms of stature changes and is thought to represent compression of intervertebral discs due to increased spinal loading (Bonney & Corlett, 2002). Acute spinal shrinkage is associated with postural discomfort (Beynon & Reilly, 2001), and neck posture may be particularly important. As the head moves forward relative to the torso, the gravitational load on the spine increases (Vasavada et al., 2015). However, if the head is extended relative to the torso, this can also lead to neck shortening (Frantz et al., 2021). Thus, we chose to use neck shrinkage as a plausible monotonic measure of neck compression caused by failing to maintain a neutral cervical spine.

In summary, preliminary evidence suggests that maintaining posture is related to the ability to manage attention (Baer et al., 2019), and biofeedback devices do not take limitations of attention into account in their design. By treating maintenance of posture as a task in a dual-task experiment, we investigated the attentional cost of attending to posture, along with the effectiveness of biofeedback. We hypothesized that biofeedback would (1a) improve neck length retention, while (1b) worsening computer task performance, resulting in (1c) an attentional tradeoff between a participant's ability to maintain neck length and their overall game score. Further, (2) this attentional tradeoff would be reduced in people with higher levels of mindfulness. We also predicted (3) a correlation between neck disability and neck shrinkage during the task.

Method

Participants

We tested 42 participants (20 men and 22 women) aged 18 to 24 years ($M = 19.7$, SD 1.8), recruited from psychology courses at the University of Idaho. This study was approved by the Institutional Review Board of the University of Idaho; all participants provided written informed consent and received course credit for a 2-h data collection session. Prior to testing we screened participants for physiological and psychological issues that could interfere with their ability to perform the tasks. Participants were excluded from the study if they reported current musculoskeletal injuries (pain in any part of the body while standing or walking), neurological issues (diagnosed mental disorder), or any condition that could interfere with their ability to perform the task comfortably.

Equipment

Three-dimensional motion capture data were collected using eight Vicon Bonita motion capture cameras (Oxford, UK) and processed using The MotionMonitor software by Innovative Sports Training (Chicago, IL). Vicon precision for absolute position is 0.15 mm, with a variability of 0.025 mm within a single data collection session (Merriaux et al., 2017). Thirty reflective markers were placed on bony landmarks of the body (Fig. 1), tracked by Vicon Nexus software with data streaming to The MotionMonitor for processing at a rate of 100 frames/second. The arrangement of these reflective markers produced eight body segments in Vicon: head, neck (atlanto-occipital, A/O to C7/T1 joint), upper torso (C7/T1 to T12/L1 joint), lower torso (T12/L1 to L5/S1 joint), left and right upper arm, and left and right thigh. Based on these Vicon segments, The MotionMonitor produced a composite model of each participant's skeletal structure for analysis, with joint centers determined based on offset positions from surface landmarks recorded in anatomical position (Chaffin et al., 2006). The A/O (between the left and right mastoid process) and C7/T1 (7.18 cm forward, 3.35 cm down from the C7 spinous process) joint centers were used in analysis (Fig. 2a).

The participant workspace was equipped with an adjustable sit-stand desk, adjustable monitor display, and adjustable backless office chair (to accommodate the use

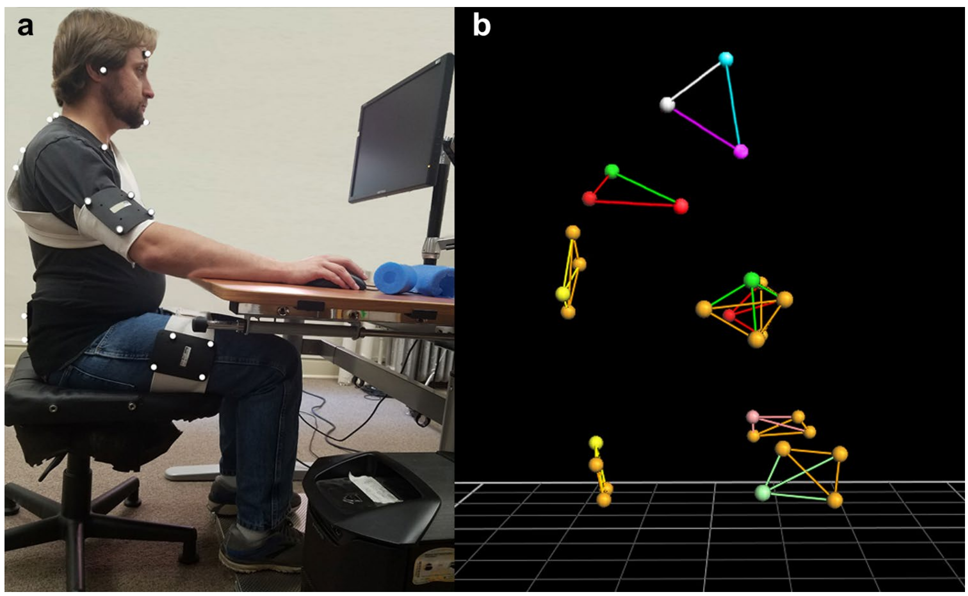

Fig. 1 Reflective markers. **a** Participant wearing reflective marker clusters for head; upper, middle, and lower torso; left and right upper arm; and left and right thigh. **b** Vicon segments produced by reflective markers shown in 1a

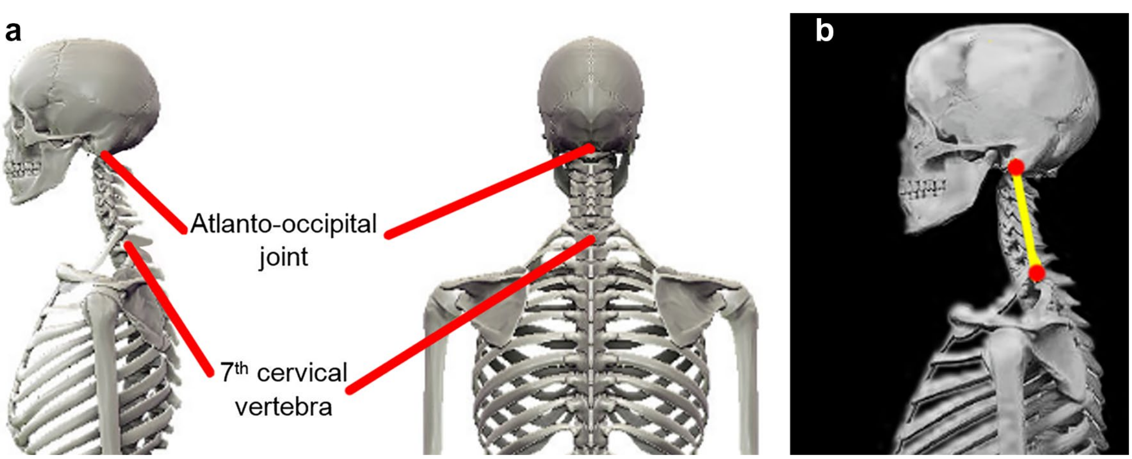

Fig. 2 Anatomical landmarks. **a** Bony landmarks used in digitization of composite skeleton. **b** The MotionMonitor composite skeleton. Digitized points for atlanto-occipital (A/O) joint and C7 are shown in red; dependent measure of relative neck length (neck shrinkage, distance between AO joint and C7 relative to best posture) are shown in yellow

of reflective markers). This allowed the workstation to be tailored specifically to each participant's anthropometry.

Protocol

First, the workstation was adjusted for each participant using standard ergonomic guidelines (Chaffin et al., 2006) such that ankles, knees, hips and elbows were at 90 degrees and the center of the screen was 10 degrees below eye level. Participants were additionally instructed to allow their heads to float at the top of their spine to maintain an uncompressed neck. After workstation adjustments were made, reflective markers were attached (Fig. 1). Participants were asked to maintain their posture as described above for 10 s for an initial baseline recording of neck length to base the biofeedback variable on.

Next, participants received a brief tutorial on the computer game (*Diner Dash 2*—Playfirst, 2006) and 5 min of unrecorded practice to mitigate possible practice effects. Participants then played two 10-min sessions of the game, once with biofeedback and once without biofeedback, in counterbalanced order. Participants were urged to see how many points they could earn in the game. Before each trial, participants were given a brief reminder about maintaining the instructed posture. After the first game session, participants were given 5 min of rest and allowed additional time if requested. After the second session, participants were asked to complete two surveys prior to being debriefed on the experiment.

Diner Dash 2 is an attention-demanding computer game in which the player takes the role of a waiter in a busy diner; performance is scored based on how players manage important hierarchical decisions in parallel over time. Because the game only requires mouse controls (no keyboard input), participants never have to look away from the screen (which would interfere with posture). The game uses second-order controls, which leads to delayed feedback and increased cognitive load (Sanders & McCormick, 1993); players click on a screen location with a task, and the waiter travels to that location at a set pace before any action can be completed. The game also challenges users with a graphically complex display, which further increases cognitive load (Bennett & Flach, 1992); the display is dynamic and uses abstract representations to indicate each goal (seating customers as they line up, taking orders as customers become impatient, serving orders as they pile up in the kitchen, bussing tables and serving bills to create reasonable turnover for customers).

Players are scored based on how many tables of customers are fully served, with bonus points awarded for customer satisfaction at the end of their meal. Each customer begins with three hearts, losing one each time an action takes too long to complete. The game ends if five customers leave unsatisfied. Customers arrive in groups of one to four, at an increasing rate as the game progresses. To achieve high scores (about twenty thousand), users must demonstrate cognitive competency by responding quickly to the changing environment (visuomotor performance), completing tasks in parallel (parallel information processing), and remembering unique customer types to prioritize for bonus points (prospective memory) to maximize point totals. Players who restart frequently due to failing objectives, and those who complete one continuous attempt without bonus objectives will both score poorly (below ten thousand points). This game has been modelled as a benchmark for measuring progress of policy learning algorithms, and should generalize effectively to measuring cognitive performance on visuomotor performance and prospective memory (Chen et al., 2020).

Measures

Neck shrinkage and biofeedback

As our primary measure of posture, and as a biofeedback variable, we used percentage of neck length relative to baseline (represents neck shrinkage when decreasing, and neck length retention when maintained), which helps account for anatomical differences between participants. Neck length was measured as the three-dimensional linear distance between the AO joint center and the C7/T1 joint center (Fig. 2b). We used a threshold of 97.5% of baseline to provide biofeedback to participants during tasks. We monitored posture in real time using a moving average of 10 s. If the average neck length shortened to less than 97.5% of baseline, a warning tone of 440 Hz would sound until the participant's posture was corrected (*i.e.*, returned within 97.5% of baseline). We selected this threshold based on pilot testing with 20 individuals; we asked participants to test various postures (slumped, forward head, military neck, downward gaze) and found that most participants were able to notice discomfort from approximately 1% neck shrinkage, and all participants noticed the difference at 2.5%. In addition to its use in biofeedback, neck length was recorded continuously for each 10-min trial. We used the moving average across a 10 s period to account for head movement and occasional glances away from the screen.

Computer game

The Diner Dash game awards points based on speed and number of actions taken. After a loss total scores are reported, and the game can be restarted quickly. Total game score across all attempts for 10 min was used as a measure of performance. Additionally, game scores were used to calculate a cognitive dual-task effect from the use of biofeedback (McIsaac et al., 2015). This measure quantifies the percent change in score between attempts on the task with and without biofeedback using the equation: (score with no feedback—score with biofeedback)/(score with no feedback × 100). This measure represents the attentional cost of biofeedback; a greater percent change indicates a greater decrement in performance on the task. All participants were given 5 min of practice to familiarize them with the game mechanics to control for possible practice effects. Participants were also asked about their previous experience playing computer games as well as specific experience with Diner Dash 2.

Questionnaires

The Neck Disability Index (NDI, Vernon & Mior, 1991) is a self-report measure of a person's perceived neck pain and its effect on their daily life. While we did not specifically recruit participants who were suffering from or being treated for neck pain, we include this measure because young adults are at high risk for neck pain (Haldeman et al., 2010), and the questionnaire is sensitive enough to detect minimal neck pain that may otherwise go unreported (Jorritsma et al., 2012). The NDI consists of 10 questions addressing pain intensity, personal care, lifting, reading, headaches, concentration, work, driving, sleeping, and recreation. For each of these categories, participants mark the statement that best matches their perceived neck disability within that category, on a scale from "not at all disabling" to "severely disabling." Each item is scored from 0 to 5 and the total score is doubled to calculate a percentage which indicates to what degree their life is affected by neck pain, with a higher score indicating more pain and disability.

The Mindful Attention Awareness Scale (MAAS, Brown & Ryan, 2003) is a 15-item questionnaire designed to assess awareness of and attention to what is taking place in the present. Each item describes a symptom of unawareness (e.g. pain awareness, reading, or sleeping) participants indicate how frequently they experience that phenomenon (1 for almost always, 6 for almost never). The final score is tallied and used to describe a person's self-reported level of mindfulness, where a higher score indicates more mindfulness.

Statistical analysis

Data from The MotionMonitor were processed using custom code written in MATLAB R2017a; ANOVAs and correlations were conducted using SPSS Version 22. Relevant population parameters for game score, baseline neck length, MAAS scores, and NDI scores are displayed in Table 1. NDI scores were not normally distributed; the distribution was skewed towards lower neck pain scores; this reflects that our sample population was not recruited for neck pain.

To test the hypothesis (1a) that biofeedback would facilitate neck length retention, we conducted a 2 × 2 × 5 mixed ANOVA with factors for testing order (biofeedback first or no biofeedback first; between-groups), condition (biofeedback or no biofeedback; repeated-measures), and time (2-min intervals; repeated-measures). Post hoc comparisons were performed to assess the simple effect of condition in each testing order (paired t tests) and the simple effect of time in each condition and across each testing order (four separate 1 × 5 ANOVAs). To test the hypothesis (1b) that biofeedback impairs computer task performance, we conducted a 2 × 2 mixed ANOVA with factors for order and condition as above.

To assess whether the results demonstrated a tradeoff between posture and cognitive performance (hypothesis 1c), we correlated the cognitive dual-task cost for each participant to their average neck length retention during the task with biofeedback. To test the hypothesis (2) that the attentional tradeoff would be reduced in people with higher mindfulness, we correlated MAAS scores to dual-task cost, average neck length percentage during each condition (biofeedback and no feedback), and the change in neck length over time (slope, in units of percent/10 min). To test the prediction (hypothesis 3) that neck pain would be associated with deviations from neutral posture during computer tasks, we correlated participants' NDI scores to their average neck length percentage and neck length slope. To determine if the cognitive tradeoff was related to neck pain, we correlated the cognitive dual-task cost with NDI score.

Table 1 Population parameters for each measure used in analysis

Variable	Mean	SD	Skewness
Baseline neck length	14.3 (cm)	1.9 (cm)	–0.39
Average game score	20,101	6275	0.51
MAAS score	61.2	9.2	–1.11
NDI score	8.3	6.8	1.46*

Neck length measured during baseline (cm), average game performance (score), Mindful Attention Awareness Scale (MAAS) score, and Neck Disability Index (NDI) score. Includes mean (column 1), standard deviation (column 2), and skewness (column 3)

*NDI scores were not normally distributed; the distribution was skewed towards lower neck pain scores; this reflects that our sample population was not recruited for neck pain

Results

Data from five participants were removed due to unreliable motion capture data (several minutes of missing data due to poor marker visibility). Data from two participants were removed because game scores were greater than 3 standard deviations above the average. We analyzed data from the remaining 35 participants.

Neck length measure

Neck length retention is shown in Fig. 3a. Time spent playing the game led to neck shrinkage of 2.0% overall, $F(4, 128) = 4.77$, $p = 0.001$; contrasts revealed that neck shrinkage occurred after 6 min of play ($p < 0.01$) and shrinkage continued to increase after 8 min of play ($p = 0.03$). Condition also had an effect; neck shrinkage was 1.8% greater without biofeedback than with biofeedback, $F(1, 32) = 37.24$, $p < 0.001$. There was an interaction between condition and testing order, $F(1,32) = 8.8$, $p = 0.01$. Post hoc tests of simple effects showed no effect of testing order in the biofeedback condition, but there was a significant effect in the no feedback condition, $p = 0.03$, demonstrating that participants had less neck shrinkage without feedback if they performed the task with biofeedback first. There was also an interaction between condition and time, $F(4, 128) = 3.68$, $p < 0.001$, demonstrating that without biofeedback neck shrinkage occurred over time: $F(4,132) = 8.80$, $p < 0.001$, but with biofeedback it did not: $F(4,132) = 0.41$, $p = 0.8$. There were no three-way interactions.

Cognitive measure

Game performance

Game performance is shown in Fig. 3b. Condition influenced game score, $F(1,31) = 5.0$, $p = 0.03$, such that score was worse when participants performed the task with biofeedback than when they performed without biofeedback. There was also a significant interaction with testing order, $t(16) = 4.2$, $p < 0.001$; such that participants who played the game with biofeedback first did worse during the biofeedback condition than the no feedback condition. When playing the game with no feedback first, there was no difference in score between conditions.

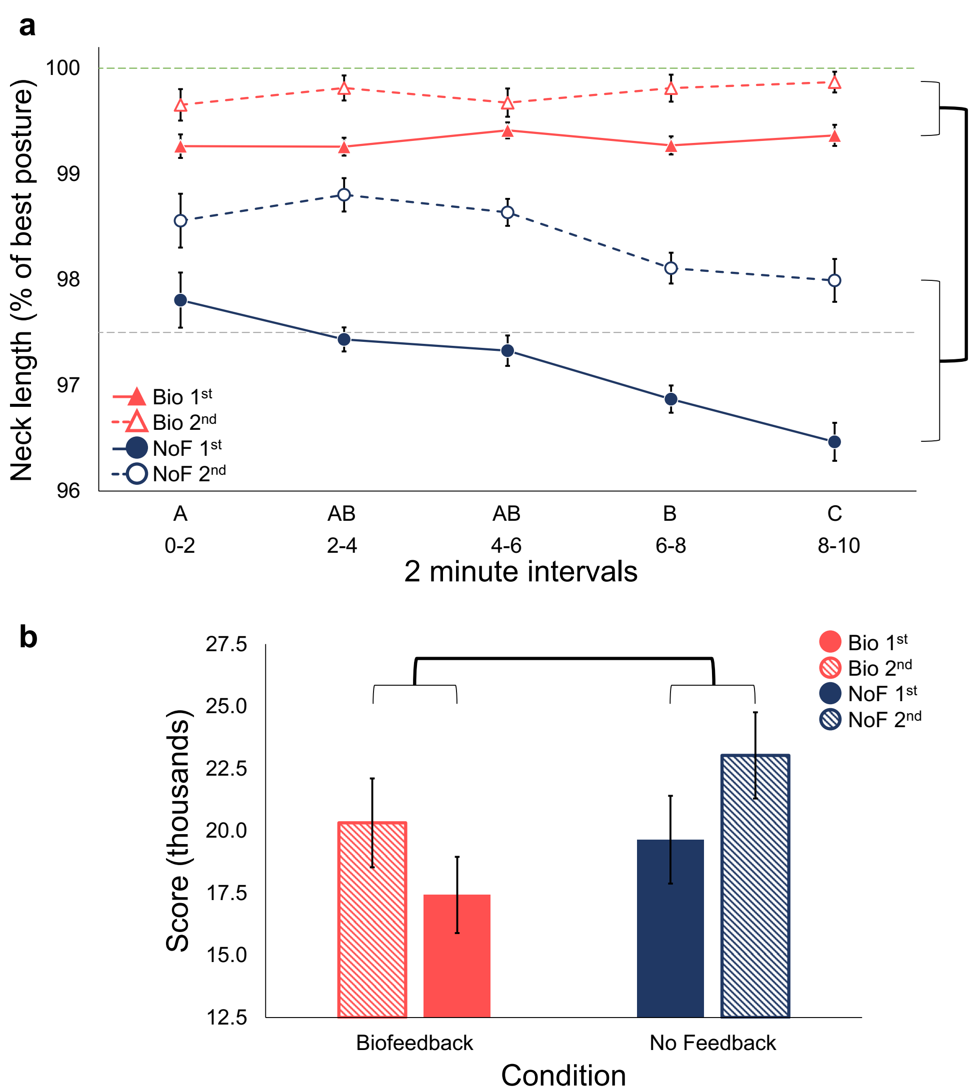

Fig. 3 Effects of biofeedback. **a** Neck length biofeedback reduces neck shrinkage. Neck length as percent of best posture (*y*-axis) over 2-min intervals during the computer task (*x*-axis); when using biofeedback (red triangles), and without biofeedback (blue circles), divided to show order effects (solid shape and line for first trial, empty shape and dashed lines for second trial). Lettering on the *x*-axis represents contrast groups for time playing the game, indicating significant differences between 0–2 and 6–8 min and between all previous time periods and 8–10 min. **b** Biofeedback negatively impacts task performance. Game score between conditions (red at left: biofeedback, blue at right: no feedback); shaded bars indicate condition order (solid: first attempt; striped: second attempt)

Correlation between cognitive and neck length data

Dual-task cost correlated with neck length percentage during biofeedback

Dual-task cost correlated with neck length percentage during biofeedback, as seen in Fig. 4. Dual-task cost of biofeedback to game score was negatively correlated with average neck length percentage when playing the game with biofeedback, $r(33) = -0.44$, $p = 0.008$. When playing the game and maintaining posture with biofeedback, participants who had a smaller cognitive dual-task cost had better neck length retention than those with a larger dual-task cost. Dual-task cost did not correlate with NDI or MAAS scores. Table 2 shows a complete correlation matrix for all measures.

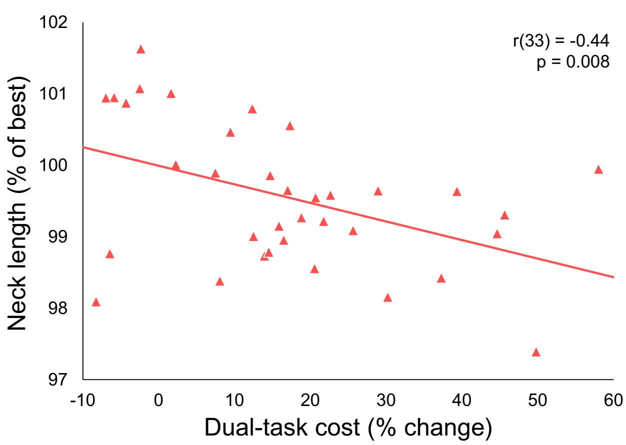

Fig. 4 Dual-task cost correlates negatively with neck length retention. Graph of correlation between average neck length (as a percentage of best posture) with biofeedback (*y*-axis), and dual-task cost to game score as a result of biofeedback (*x*-axis)

Correlations between survey measures and neck length data

Survey measures

Average score on the MAAS was 61.2 (SD = 9.2). Average score on the NDI was 8.34 (SD = 6.8). There was no difference in score on either measure between participants who played the game first with biofeedback or without.

Neck length slope during the task correlated with MAAS

Neck length slope during the task correlated with MAAS, as seen in Fig. 5a. MAAS scores positively correlated with neck length slope during the task without feedback, $r(32) = 0.52$, $p < 0.001$. Participants who reported higher mindfulness had better neck length retention (less negative slope) during the task without biofeedback than participants who reported lower mindfulness.

Neck length slope during the task correlated with NDI

Neck length slope during the task correlated with NDI, as seen in Fig. 5b. Neck disability scores negatively correlated with neck length slope during the task without feedback, $r(32) = -0.50$, $p = 0.001$. Participants who reported greater neck pain disability in their daily life had more neck shrinkage during the task without feedback than participants who reported less neck pain disability in daily life.

Table 2 Correlations between measures with and without biofeedback

	Dual-task cost	MAAS score	NDI score	Neck length % (biofeedback)	Neck length % (no feedback)	Neck length % slope (no feedback)
Average game score	–0.20	0.01	0.29	0.26	0.31	0.24
Dual-task cost		0.1	0.25	0.44*	NA[a]	NA[a]
MAAS score			–0.39*	–0.09	0.13	0.52*
NDI score				0.03	–0.12	–0.50*
Neck length % (biofeedback)					0.53*	–0.19
Neck length % (no feedback)						0.01

Each cell contains the Pearson's product-moment correlation coefficient (*r*-value) relating variables on each axis. Variables are average game score, dual-task cost to game score, Mindful Attention Awareness Scale (MAAS) score, Neck Disability Index (NDI) score, average neck length relative to baseline, and slope of neck length over 10 min.

*Statistical significance.

[a]Not computed because without feedback there is no dual task and thus no dual-task cost

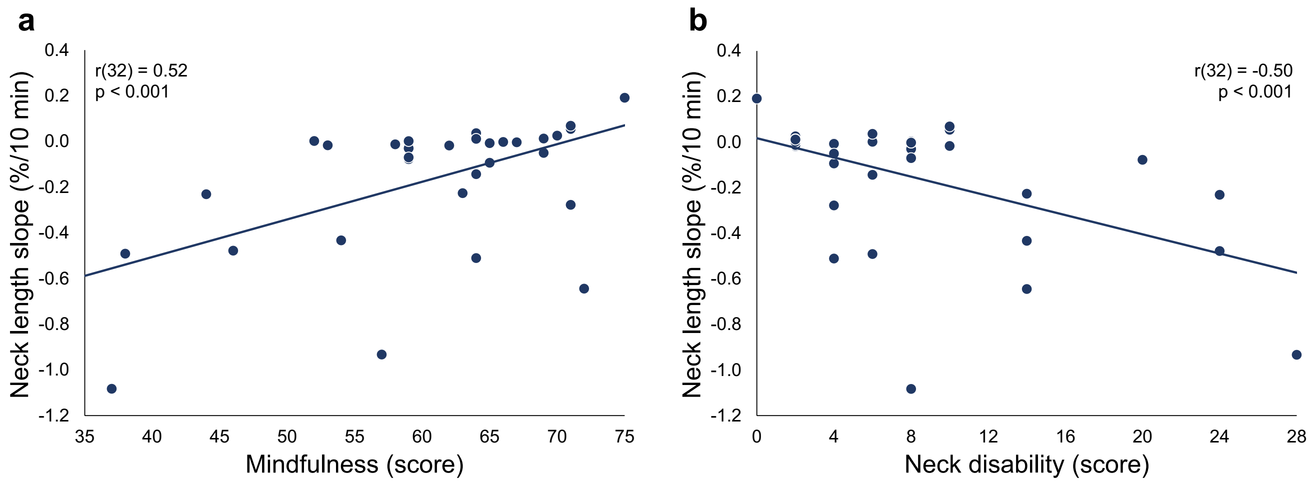

Fig. 5 Slope of change in neck length over time correlates positively with self-reported mindfulness and negatively self-reported neck disability. **a** Correlation between the slope of change in neck length over 10 min of play without feedback (*y*-axis, % change in neck length/10 min, negative numbers represent neck shortening over time) and score on the Mindful Attention Awareness Scale (*x*-axis). Higher mindfulness was associated with greater retention of neck length. **b** Correlation between the slope of change in neck length over 10 min of play without feedback (*y*-axis, % change in neck length/10 min, negative numbers represent neck shortening over time) and score on the Neck Disability Index (*x*-axis). Higher neck pain was associated with lower retention of neck length

Discussion

Summary of findings

This study demonstrated that posture biofeedback creates a cognitive load that interferes with performance of a challenging cognitive task. While biofeedback did improve neck length retention during an attention-demanding computer game, participants' game scores were significantly worse during the biofeedback condition than without biofeedback, indicating a dual-task cost. Dual-task cost correlated with neck length percentage during the task while using biofeedback, suggesting a relationship between the two. In addition, higher self-reported mindfulness was correlated with neck length retention without the use of biofeedback. Finally, higher neck disability scores were correlated with greater neck shrinkage without the use of biofeedback.

Interpretation

Posture is hard to change

Poor working posture is widespread despite the numerous physiological drawbacks (DHHS, 1997; Griegel-Morris et al., 1992; Hlavenka et al., 2017; Murray et al., 2013). Why might this be so? The relationship seen here between the increased dual-task cost of biofeedback and the greater neck shrinkage during the biofeedback condition suggests that to change poor habitual posture, not only is attention to feedback required, but those with worse postural habits incur a greater attentional cost as a result. Thus, there is a built-in deterrent preventing those with poor postural habits from *actively* attending to their posture to correct it. This poses a practical problem; if performance on the primary task worsens with biofeedback users may become frustrated, leading to low compliance, and ultimately not reducing neck pain.

Cognitive-motor tradeoffs are frequently observed in studies of gait and balance (Hawkes et al., 2012; Huxhold et al., 2006; Mirelman et al., 2012; Yogev-Seligmann et al., 2008) but have not previously been observed in studies of posture. We recently found evidence for a *motor*-motor tradeoff involving posture and anticipation of gait (Baer et al., 2019); the present study is the first to demonstrate a *cognitive*-motor tradeoff in a study of neck length. These results provide the first evidence that attention is important for managing neck posture.

Mindfulness may facilitate the use of intrinsic biofeedback

Mindfulness is important for maintaining awareness of one's physiological state (Sze et al., 2010). It has been proposed that individuals with forward neck posture and neck pain are not aware of their postural deviations (Edmondston et al., 2007; Lee et al., 2014); thus, they may not be as mindful as others. Furthermore, more mindful individuals have been shown to have less flexed neck posture (Baer et al., 2019). While mindfulness did not relate to dual-task performance cost in the present study, it did relate to how well participants maintained their neck posture without feedback. This suggests that rather than contributing to active management of attention during dual-task performance, mindfulness may *automatically* bring attention to subtle changes in posture, facilitating the use of intrinsic feedback (Lutz et al., 2009).

Intrinsic feedback comprises internally generated cues that provide information on the internal state of an individual (Patchan & Puranik, 2016). One source of intrinsic feedback may be proprioceptive information related to shortening of the neck. Our results suggest that unlike extrinsic biofeedback, intrinsic feedback based on neck proprioception does not come with an attentional cost. In other words, using external feedback seems to be attentionally expensive, while using internal feedback seems to be more economical. Previous research has demonstrated that extrinsic feedback distorts timing for distinct events; responding to the external sound of a keypress produces less accurate timing estimates than responding to the internal proprioceptive feedback of the keypress (Cao et al., 2020). This implies that intrinsic feedback is less affected by mental noise compared to extrinsic feedback. Thus, greater mindfulness may enable better discernment of intrinsic feedback by reducing mental noise.

Also of note, participants with greater neck shrinkage during the task without feedback reported more neck pain in their daily lives. It is possible that participants who are less sensitive to immediate discomfort from shortening of the neck are more predisposed to long-term neck pain as a result of poor postural habits, because they are not using intrinsic feedback to automatically sense and correct their posture.

Practical implications

In the present study, everyday neck pain was associated with neck shrinkage during a computer task. This may be because neck shrinkage reflects compression of the neck, which is representative of soft tissue damage associated with poor posture. However, commercially available postural biofeedback devices rely solely on angle measurements. Future postural biofeedback device development should consider incorporating measures of shrinkage.

While using biofeedback to improve posture may be reasonable in office work, it is not feasible in every workplace. For instance, surgeons, dental technicians, and heavy machine operators often have similar postural complaints to those in office work, but they may be unable to implement biofeedback interventions because these situations require focused attention to avoid making potentially dangerous or even fatal mistakes. Therefore, the reduced computer task performance associated with posture biofeedback could be a serious problem.

Cultivating the use of intrinsic feedback may be an important approach to improve posture. Embodied disciplines such as Alexander technique (Becker et al., 2018; MacPherson et al., 2015) and Tai Chi (Lauche et al., 2016) incorporate elements of mindfulness training along with practice attending to body positions and muscle tensions during activity. Thus, embodied mindfulness practices may enhance responsiveness to intrinsic feedback, and practitioners may become more able to effectively identify suboptimal postures. Another possible benefit of embodied mindfulness approaches is that they focus on improving postural habits, rather than providing frequent feedback about alignment as typical biofeedback does. A change in habit could reduce dual-task costs and subsequent frustration from reduced performance.

Strengths and limitations of the study

Strengths

While dual-task designs are frequently used to study the impact of combining cognitive tasks with gait and balance tasks, this is the first application of the dual-task paradigm to demonstrate a tradeoff between cognitive performance and maintenance of posture. In addition, the use of a computer game in this context allowed us to emulate a real-life situation where this tradeoff may occur. Furthermore, our use of relative neck length as a measure of posture allows us to define biofeedback outcomes in monotonic terms (shorter is worse) across participants. This stands in contrast to methods that rely on angles, which interact unpredictably with one another (e.g., the neck may flex with respect to the trunk and the head angle may extend with respect to the neck, resulting in different spinal loads) and do not have universally—or objectively—defined ideal values. Finally, our inclusion of mindfulness as a variable sheds light on how individuals attenuate the attention demands of managing posture and opens a conversation about the possible role of intrinsic feedback in managing posture while performing concurrent tasks.

Limitations

Previous studies of posture in the workplace have relied on angular measures such as forward head posture. Because this is the first study using neck length percentage as a measure of posture, it is difficult to directly relate our results to previous studies.

In addition, the use of game score as an overall measure of dual-task cost did not allow us to attribute performance differences to underlying cognitive factors. It would be valuable to repeat this study using measures for specific cognitive factors like reaction time or inhibitory control, both of which and are known to be affected by dual-task costs and have previously been associated with posture (Baer et al., 2019; Fujiwara et al., 2009).

Finally, use of biofeedback to maintain posture has been shown to be more effective with a longer training period. The short training period with the task and biofeedback may not have been enough to understand the dual-task impact when either task is well rehearsed. It is possible that when concurrent cognitive tasks are less challenging or more well learned, the elevated cognitive costs of biofeedback seen here in people who deviated more from neutral posture will be reduced (Verhaeghen & Cerella, 2002).

Conclusion

The use of postural biofeedback during a computer task increased cognitive load. Biofeedback improved neck length retention while hampering computer task performance, demonstrating a dual-task tradeoff. This effect was strongest in the subjects who received the most feedback (i.e. those with the worst postural habits), indicating that those with the greatest need for postural feedback also suffer the greatest computer task performance decrements from extrinsic postural feedback. In contrast, subjects with higher self-reported mindfulness maintained their posture better without feedback, indicating that mindfulness may promote the use of intrinsic feedback, reducing reliance on extrinsic biofeedback. Therefore, interventions that target mindfulness may benefit posture and in turn reduce neck pain, without compromising task performance.

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Data availability Data collected for this study and the associated pilot testing are available by request through the corresponding author and Mind in Movement Lab at the University of Idaho.

Code availability Proprietary software and hardware provided by Innsport for use with The Motion Monitor system was used to collect data. Additional custom code used to collect data via 3-dimensional motion capture, and Matlab code used for data analysis is available by request through the corresponding author and Mind in Movement Lab at the University of Idaho.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethics approval The experiment and pilot data published herein have been approved by the University of Idaho IRB. The procedures used in this study adhere to the tenets of the Declaration of Helsinki and its later amendments.

Consent to participate All participants provided written informed consent, and received course credit for a two-hour data collection session.

Consent for publication All participants provided consent to publish data and images associated with the study when agreeing to participate in this study.

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