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Effects of biofeedback on secondary-task response time and postural stability in older adults

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Abstract

Real-time single- and multiple-axis vibrotactile feedback of trunk motion has been shown to significantly decrease mean trunk tilt and decrease time spent outside a no vibrotactile feedback zone (dead zone) in older adults within a laboratory setting. This study aimed to determine if these improvements can translate into everyday use, during which other tasks may simultaneously demand attention. A dual-task paradigm was used in which 10 community-dwelling older adults were asked to perform standing trials in the presence of a secondary task (verbal or push-button), vibrotactile feedback, or both (dual-task). Results show that subjects significantly increased the percentage of time inside the dead zone when feedback was provided compared to when it was not during both verbal (+13.6%) and push-button (+10.1%) secondary tasks. Providing feedback also decreased RMS of trunk tilt during both secondary tasks (verbal: -0.1298; push-button: -0.1388). However, response times for secondary tasks increased (verbal: +119 ms; push-button: +110 ms) when feedback was provided. These results suggest that while vibrotactile feedback does increase attentional load in older adults, it can still be used effectively to improve postural metrics in high cognitive load situations.

1. Introduction

A frequent explanation for the decrease in postural sway observed with vibrotactile feedback devices is that these devices augment intact native sensory inputs, giving the user more information about body position with respect to gravity [1–8]. The cues delivered by vibrotactile feedback provide an external reference of verticality and are similar to those considered responsible for the improvement in balance observed when a user lightly touches a cane [9]. Research in dual-tasking, however, has suggested that the improved balance afforded by light touch and other traditional mobility aids may come at the cost of increased cognitive load and decreased secondary task performance [10,11]. On the other hand, studies augmenting other sensory modalities have yielded encouraging results under dual-task conditions. For example, Downs demonstrated that using a hearing aid, which amplifies auditory input, not only increases performance on speech discrimination (primary task), but also improves performance on a secondary task [12]. In that study subjects were told to turn off a light, as quickly as possible, that turned on randomly throughout the trial. Downs

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posited that hearing aids reduce the cognitive demands of the primary task and allow subjects to allocate more attention to the secondary task.

Increased cognitive load presents a particular challenge for older adults as they show not only increased postural sway under such conditions [13–16] but also decreased secondary task performance [13,17]. This exhibited decrease in dual-task performance for older adults is often attributed to decreased sensory information [14,17], suggesting that sensory augmentation may be beneficial. However, if there is a corresponding increase in cognitive load when using sensory augmentation, vibrotactile feedback may further decrease dual-task performance.

A recent gait study by Verhoeff et al. used two different secondary tasks, one motor (carrying a tray with cups of water) and the other cognitive (counting backwards by 7 s), to evaluate the ability of older adults to use multi-modal feedback (tactors, audio alarms, and lights) during dual-tasking [6]. For the motor task trials, trunk sway velocities decreased when feedback was provided. This reduction, however, was confounded by a significant increase in trial time (i.e., subjects took longer to complete the dual-task trials); lower gait velocities may have contributed to the decrease in trunk sway velocities. For the cognitive task trials, gait showed no improvements although cognitive task performance improved. However, the longer length of the dual-task trials could have inflated the improvements observed in secondary task performance.

Recognizing that separate investigations have reported opposite findings for the influence of sensory augmentation on cognitive load, the aim of this study was to assess the effects of vibrotactile feedback on dual-tasking for older adults by using standing balance and response time tasks. We first compare balance metrics with and without feedback during secondary tasks to determine if older adults can effectively use vibrotactile feedback while multitasking. We then analyze the response times of the secondary task with and without feedback to quantify the attentional demands of feedback.

2. Methods

2.1 Participants

Ten (6 male and 4 female) community-dwelling older adults ranging in age from 68 to 80 (74 ± 4.3 years) volunteered to take part in the study. The Institutional Review Board at the University of Michigan approved the experimental protocol and informed consent was obtained from each subject in conformance with the Helsinki Declaration. In order to participate, subjects were required to be free of any central neurologic or musculoskeletal dysfunction and not suffering from frequent back or lower extremity pain. Subjects were also excluded if they self-reported a hearing deficit, nerve damage, numbness in their feet, severe visual impairment, a history of fainting, or had a body mass index greater than 30 kg/m^2. Before testing began, a Semmes–Weinstein monofilament test [18] was used to rule out peripheral neuropathy.

2.2 Instrumentation

The vibrotactile feedback device comprised a belt, an inertial measurement unit (IMU, Xsens Technologies B.V. Enschede, The Netherlands), four vibrating actuators referred to as tactors (C-2 Engineering Acoustics Inc., Casselberry, FL, USA), and a laptop. The belt was worn around the subject's trunk at approximately the L3 level. The IMU was positioned on the outside of the belt near the spine and collected tilt data in the anterior–posterior (AP) and medial-lateral (ML) directions at 100 Hz. The tactors, which provided vibrotactile feedback, were located on the inside of the belt and were positioned at the cardinal points: 12, 3, 6, and

9 o'clock, where 12 o'clock is aligned with the navel and 6 o'clock with the spine [5]. The laptop was used to generate auditory tones for the secondary tasks.

Feedback was provided when the control signal exceeded the dead zone. The control signal was approximately proportional to the estimated trunk tilt angle. Subjects were asked to stand upright during IMU calibration, thus setting the zero point. For all subjects, the dead zone was set to 0.8 in the ML direction for the two experimental stances (normal and semi-tandem Romberg), 1.0 in the AP direction for normal stance, and 2.0 in the AP direction for semi-tandem Romberg. Subjects received a vibration from the tactor most closely aligned with the direction of trunk motion once their trunk position exceeded the dead zone. Only one tactor fired at a time. Vibrations were provided at a 20 Hz beat frequency produced by combining two square waves of 250 and 270 Hz [19].

Two secondary tasks (described below) were used in this experiment; during both tasks, tones of two different frequencies [20] (440 and 1000 Hz for eight of the subjects; two subjects had difficulty distinguishing high and low so tones were changed to 200 and 500 Hz) were generated by the laptop and played through speakers for one second. For the first task, which required verbal responses, a microphone was used to record subjects' responses. For the second task, two hand-held push buttons were used to capture responses and the consequent voltage signals were recorded via the laptop.

2.3 Experimental Procedure

Subjects were provided with a set of uniform exercise pants and shirt prior to donning the vibrotactile feedback device. Before the experimental procedure began, subjects completed two 30-s baseline trials with bare-feet shoulder-width apart (normal stance) and eyes open. Next, subjects were trained with the vibrotactile feedback device and the secondary tasks for a total of 20 min. The feedback training was performed to ensure they could feel each tactor and knew how to interpret and respond to the vibrations. Subjects were instructed to stand as still as possible and to move away from the vibrations when they received them (i.e., tactors provided repulsive cues). Subjects then received training for the secondary tasks, which were both choice response tasks. Two tone pitches (“high” and “low”) were played randomly throughout each trial, with eight tones typically played for each trial. The minimum and maximum time intervals between tones were 1 and 5 s, respectively. Subjects were asked to identify whether the tone was “high” or “low” [21] and respond as quickly as possible. In verbal trials subjects were instructed to respond verbally, saying “high” or “low”. For push-button trials, subjects responded by pressing the left button to indicate high tone and the right button to indicate low tone. Experimental conditions were stance (normal, semi-tandem Romberg), visual condition (eyes open, eyes closed), feedback (on, off) and secondary task (none, verbal, push-button). There were 24 combinations of experimental trials; each subject completed two 30-s trials of each combination for a total of 48 trials. During all trials an assistant remained behind the subject to provide assistance in the event of a loss of balance.

2.4 Data Analysis

2.4.1 Postural metrics—The IMU provided tilt estimates in the AP and ML directions which were then used to calculate total tilt according to:

$$\text{Total Tilt}^2 = AP^2 + ML^2$$

A total tilt of zero would indicate the subject is standing upright [5]. For each trial, the root-mean-square (RMS) of AP, ML and total tilt were computed by taking the square root of the time average of the squares:

$$\text{RMS}=\sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n}}$$

Percent time in dead zone (PZ) was calculated as the fraction of time during the trial that the tilt was in the dead zone times a factor of 100.

2.4.2 Response time—Audio data from the verbal responses were filtered using multi-band spectral subtraction [22] and 7th order Butterworth notch filters to remove noise and signal tones. Verbal responses were defined as beginning when the amplitude of the audio signal exceeded two-and-a-half times its standard deviation during the first two seconds of recording (which never contained tones or responses). Push-button responses were defined as beginning when the voltage first crossed a baseline threshold of 2 V. All responses were identified as: no response (1%), correct (96%), incorrect (1.5%), or corrected (subject initially answered incorrectly but then corrected him/herself; 1.5%); however, only correct responses were included in the analysis. Response time (RT) was defined as the time between the beginning of the tone and the beginning of the response (Fig. 1).

Dual-task trials were defined as those in which the feedback system was on while a secondary task was performed. Because tactor activation and secondary task were not synchronized with each other, only a few tones in dual-task trials coincided with feedback delivery (see Fig. 1). Another consideration was that subjects were not informed prior to the start of the trial whether feedback would be turned on or off. Subjects became aware of the feedback status once an initial vibration was provided. It is possible that subjects might have changed their dual-task strategy once they realized that the tactors could activate at any time. Therefore, RTs of tones before feedback was first delivered (naïve) were compared to those after the tactors were first activated (non-naïve). Thus, response times were categorized based on whether the response was naïve and whether the tactors were activated during the tone (Fig. 1). If feedback was not turned on during a trial, all RTs within that trial were labeled “FB_{off}”. If feedback was on but had not been delivered yet the RTs were labeled “$\text{FB}_{\text{on/naïve}}$. If feedback had previously been delivered (non-naïve) but was not concurrent with the response, the RTs were labeled “$\text{FB}_{\text{on/inact}}$” and if feedback was delivered, the RTs were labeled “$\text{FB}_{\text{on/act}}$”. According to this naming scheme, only $\text{FB}_{\text{on/act}}$ RTs represented a dual-task.

2.5 Statistical analysis

Statistical analysis on PZ was performed using SAS software, Version 9.1 (SAS Institute, Inc., Cary, NC). All other statistical analysis was performed using PASW Statistics, Release Version 17 (SPSS, Inc., Chicago, IL). For both analyses a linear mixed model was used with repeated measures. Means were analyzed, and stance (normal, semi-tandem Romberg), vision (eyes open, eyes closed), feedback (on, off), secondary task (none, verbal response, push-button response) and tone type (FB_{off}, $\text{FB}_{\text{on/naïve}}$, $\text{FB}_{\text{on/inact}}$, $\text{FB}_{\text{on/act}}$), were treated as factors. All main effects and interactions were analyzed. When post hoc analysis was required, Bonferonni corrections were used.

3. Results

3.1 Postural metrics

Fig. 2 shows the results of the PZ analysis. There was a significant interaction between feedback and secondary task. To confirm that subjects were still able to use vibrotactile feedback to increase PZ while performing a secondary task, data were first separated into three groups by secondary task. In all three conditions PZ increased significantly for feedback-on trials in comparison with feedback-off trials (verbal: +13.6%, $p < 0.001$; push-button: +10.1%, $p = 0.007$; no secondary task: +28.9%, $p < 0.001$). Next, the data were separated into two groups by feedback condition, which revealed a significant effect ($p = 0.002$) of secondary task during feedback-off trials. PZ increased when verbal (+14.2%) and push-button (+14.4%) secondary tasks were performed compared to no secondary task. This was not significant for feedback-on trials.

A similar analysis was performed on RMS of trunk tilt. RMS significantly decreased for feedback-on trials compared to feedback-off during push-button (-0.1388, $p = 0.044$) and no secondary task (-0.4178, $p < 0.001$) and trended but did not reach significance for verbal (-0.129, $p = 0.062$) trials. After the data were split by feedback condition, a post hoc analysis showed a significant effect of secondary task ($p = 0.023$) during feedback-off trials: RMS decreased during verbal (-0.2108) and push-button (-0.1998) secondary task compared to no secondary task. This was not significant when feedback was on.

3.2 Response time

Response times were enumerated according to two paradigms (Fig. 1). First, response times were enumerated by order of presentation within each trial (event). Next, the data were separated into eight groups by secondary task and tone type (two secondary tasks × four tone types) and then numbered by order of presentation throughout the entire session (index). An initial analysis revealed that the first event and index were significantly longer than the other RTs ($p < 0.001$); however, none of the subsequent RTs were significantly different from each other ($p = 1.000$). For this reason, the first event and index were removed from the analysis. The number of tones recorded in each tone type after the first event and index were removed are given in Table 1. Subjects 7 and 10 had less than 10 RTs for the $FB_{on/act}$ condition and were removed from the response time analysis.

RTs were not significantly different from each other ($p=0.127$). However, $FB_{on/inac}$ (661 ± 41 ms) was significantly greater ($p=0.002$) than both FB_{off} and $FB_{on/naïve}$. In addition, $FB_{on/act}$ (780 ± 45 ms) was significantly greater than all three other tone types. Similar results were found for push button response; FB_{off} (590 ± 49 ms) and $FB_{on/naïve}$ (554 ± 34 ms) RTs were not significantly different from each other ($p = 0.527$). $FB_{on/inact}$ (638 ± 50 ms) was significantly greater ($p < 0.026$) than both FB_{off} and $FB_{on/naïve}$ and $FB_{on/act}$ (748 ± 53 ms) was significantly greater ($p < 0.001$) than all three other tone types.

Response times were also analyzed by feedback condition (i.e., all RTs during feedback-on trials versus all RTs during feedback-on trials). There was a significant increase in RT for feedback-on trials versus feedback-off (verbal: 56.8 ms, push button: 51.8 ms, $p < 0.0001$).

Finally, as part of the statistical analysis, the distributions of response times were analyzed for normality. It was noted that, when feedback was provided and when subjects stood in semi-tandem Romberg, there was an increased normality in response time distribution compared to when they stood in normal stance, or feedback was not provided. To quantify this, the linearity of the

Q–Q plots of the four combinations of feedback and stance as well as the skew and kurtosis were tabulated and presented in Table 2.

4. Discussion

4.1 Postural metrics

The results demonstrate that when feedback was provided, subjects significantly increased PZ and decreased RMS of tilt even when dual-tasking. There was also an increase in PZ when feedback was off and secondary tasks were performed. This is in line with previous work [13] which has shown that when both the postural and secondary tasks are minimally demanding, posture improves. The secondary task distracts individuals away from the postural task and prevents them from focusing too much attention on an otherwise automated task.

4.2 Response time

There are two general conclusions from the response time analysis. The first is that simply having the device on does not affect cognitive load (i.e., naïve RTs are not significantly longer than feedback-off RTs). However, once a subject becomes aware that the device is active and that feedback can be delivered at any time, response times do increase (i.e., $FB_{on/inact}$ was significantly greater than FB_{off}). This demonstrates a change in dual-task strategy where the primary task (maintaining balance) is prioritized and consequently secondary task performance decreases. Second, vibrotactile feedback further increases response time when both tactor activation and secondary task are performed simultaneously. Vibrotactile feedback thus increases response times in two ways: by de-prioritizing the secondary task and by increasing cognitive load.

When response times, relabeled by tone, were analyzed, histograms were examined to evaluate normality. It was found that stance and tone type, both significant factors in increasing the mean response time, also increased the normality of the distributions. Response time distributions are frequently described as ex-Gaussian [23–25], a convolution of a normal and exponential distribution as opposed to the more familiar Gaussian distribution. McGill suggested that the normal distribution, described by μ and σ, represented the decision processes while the exponential, described by τ, distribution represents the residual processes [25]. Residual processes can include the time for the auditory signal to be transmitted, and once the signal is processed (decision processes), the time for the decision signal to transmit to the appropriate output (vocal or push-button) and for responses to be generated (i.e., muscle activation). However, Hohle proposed the opposite, that t represented the decision processes and m and s described the residual processes [24]. This understanding would predict that as a task increases in difficulty t would change but not m and s. Palmer confirmed this hypothesis and found that t increased as the difficulty of a task increased, and consequently, skew decreased [23]. Our results appear to corroborate the interpretation of Hohle and Palmer; we found that skew decreased as RTs increased, suggesting a greater value of t.

4.3 General discussion

The goal of the present study was to evaluate the potential of vibrotactile feedback to induce cognitive overload to which older adults are particularly sensitive. Results show that subjects were able to effectively use the feedback system to reduce postural sway even in the presence of a secondary task. However, it was also found that response times increased when feedback was present, implying that feedback does constitute an attentionally demanding task and may not be suitable for everyday use.

A significant limitation of this study was the large number of conditions (24 in all) versus the number of trials (48), which allowed only two repetitions of each condition. This limitation and the limitation of only having 10 subjects reduced the statistical power of the results. As mentioned before, subjects were only given training on the day of testing; it is possible that with long-term training the negative effects of dual-tasking may diminish. Additionally, a standard dead zone was employed for all subjects as opposed to scaling the zone based on an individual's abilities. This may have reduced the efficacy of the feedback system in reducing sway.

In this study we have shown that while users can still improve balance in dual-task conditions, their performance of the second-ary task decreases. However, with proper training the attentional demands of feedback could diminish with time. Our subjects only trained with the vibrotactile feedback for 20 min before experi-mental data were collected. This study demonstrates that feedback can be used in the presence of a secondary task even with minimal training. Dault showed that with repetitions older adults were able to decrease response times to a secondary task although postural control remained unchanged [26]. Based on results in the field of psychology which showed time sharing among both tasks [27], Dozza hypothesized that practicing with vibrotactile feedback allowed the integration to become more automated and resem-bling the body's natural incorporation of sensory inputs [28].

Additionally, Voelcker-Rehage showed that with practice older adults improved both cognitive and motor task performance during dual-tasking [29]. If subjects can reduce sway and perform the secondary task with the feedback device, this could support the exploration of real-time vibrotactile-based sensory augmentation devices. The device could also be used in a clinical setting to improve the balance and dual-task abilities of individuals. This is what Lajoie [31] and Bisson et al. [30] found with a 10 week biofeedback training program. After their training, functional balance and response times during dual-task studies decreased, demonstrating that postural control became more automated.

5. Conclusions

Older adults constitute a compelling subject population because they have mild to moderate losses in sensory, cognitive, and motor function, yet they can benefit from extrinsic cues of body position with respect to gravity. Of particular interest is whether or not balance performance will worsen when simulta-neously using feedback and performing a secondary task. In this study we demonstrate that older adults are able to improve postural metrics even when performing a secondary task, but find that this improvement is accompanied by decreased performance in the secondary task. We conclude that while vibrotactile feedback is attentionally demanding for older adults they are still able to use it effectively in situations involving cognitive load despite minimal training. Further studies should be conducted to determine the effect of long-term training on reaction times and performance in non-trained/novel secondary tasks.

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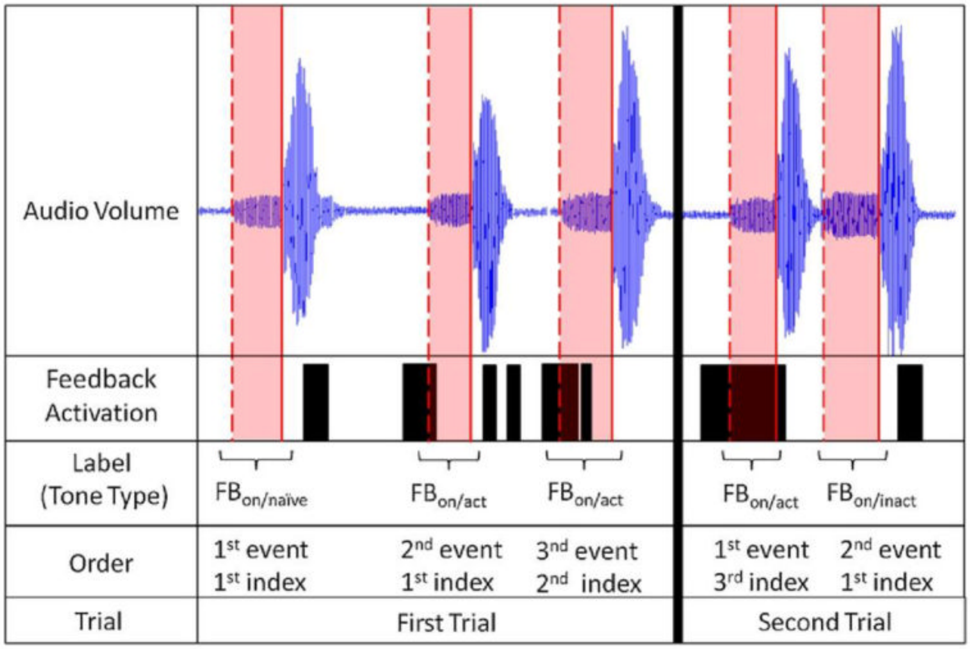

Fig. 1.

(top) Representative audio data of two feedback-on trials. Dashed lines indicate when a tone began, solid lines indicate when a response began, and response time was defined as the distance between these two points. (bottom) Feedback state, where the width of the black rectangle indicates the duration of feedback activation. Originally all tones would have been labeled feedback-on; however, only those labeled $\text{FB}_{\text{on/act}}$ had feedback activation coincide with the secondary task. Additionally, tones played before any feedback is given are relabeled $\text{FB}_{\text{on/naïve}}$ because the subject is still naïve as to whether this is a feedback-on or -off trial. For analysis purposes, tones were numbered by their appearance within each trial (events) as well as their appearance throughout the entire session (index).

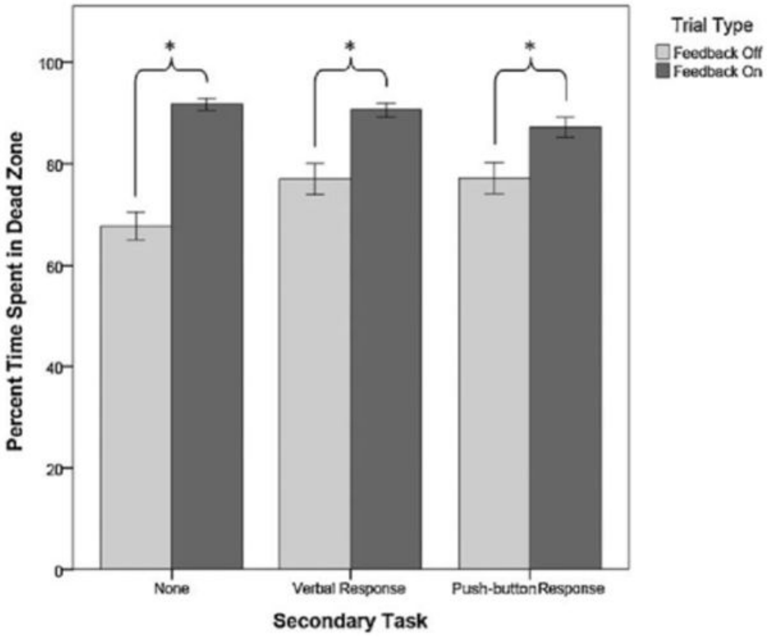

Fig. 2.

Percent time spent in the dead zone, averaged over all subjects. Percent time in the dead zone increases with feedback for all secondary task conditions. For feedback-off trials there is an increase in PZ when a secondary task is performed compared to no secondary task. * indicates significance at the 0.05 level.

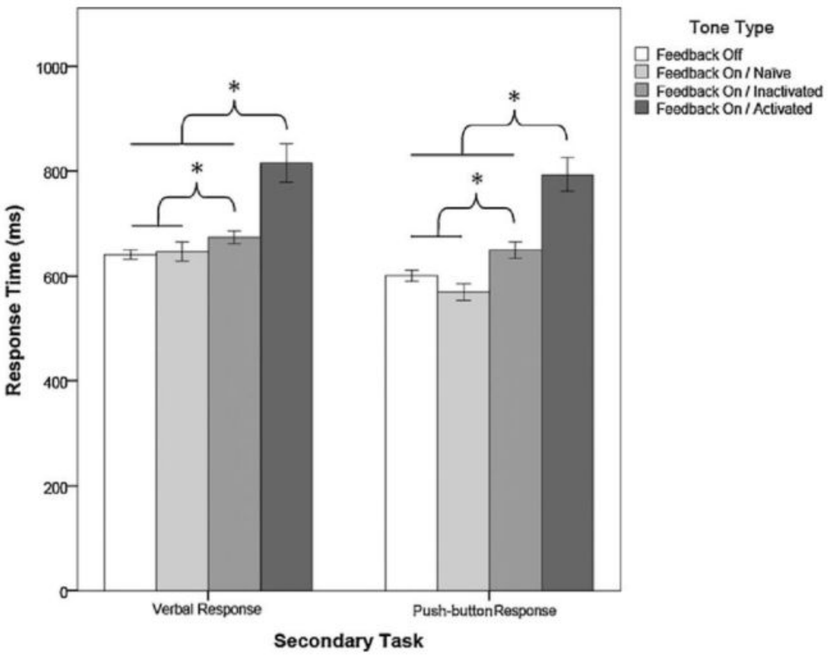

Fig 3.

Response time analysis with tone-type labeling. FB_{off} and $FB_{on/naïve}$ were not significantly different from each other in both tasks. FBon/inact was significantly greater than FB_{off} and $FB_{on/naïve}$. In addition, $FB_{on/act}$ was significantly greater than all other feedback conditions for both secondary tasks. * indicates significance at the 0.05 level.

Table 1

The number of correct responses recorded for each subject for each tone type after the first event and index had been removed. Subjects 7 and 10 had less than 10 RTs for the $FB_{on/act}$ condition and were removed from the response time analysis.

Subject	FB off	FB on/naïve	FB on/inact	FB on/act	Total	% FB on/act
1	143	36	82	13	274	4.74
2	116	24	57	27	224	12.05
3	85	23	44	17	169	10.06
4	114	39	41	19	213	8.92
5	109	21	61	22	213	10.33
6	114	28	49	25	216	11.57
7	106	41	60	2	209	0.96
8	118	13	61	34	226	15.04
9	108	40	63	12	223	5.38
10	124	51	35	8	218	3.67
Average	113.38	28.00	57.25	21.13	219.75	9.76

Table 2

Condition refers to tone type and stance condition. As dual-task condition increased in difficulty the distribution of response times decreased in skew and kurtosis and Q–Q plots increased in linearity, all indications of a more normal distribution.

Condition (Tone Type & Stance)		**Linearity**	**Skew**	**Kurtosis**
Feedback Off		0.82	2.43	10.29
Feedback On / Naïve		0.82	2.33	8.95
Feedback On / Inactivated		0.89	1.73	5.66
Feedback On / Activated	Normal Stance	0.773	2.29	6.99
	Tandem Romberg	0.928	1.13	1.88