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Effects of different physical workload parameters on mental workload and performance

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ABSTRACT

The design and evaluation of an occupational task should include an assessment of mental workload, since excessive levels of mental workload can cause errors or delayed information processing. Physically demanding work that is performed concurrently with a cognitive task may impact mental workload by impairing mental processing or decreasing performance. The primary objective of this study was to determine whether there is a differential effect of various types of physical activity on both mental workload and cognitive performance. Objective and subjective assessment tools (heart rate variability and visual analog scale) were used as indicators of mental workload, while correct responses during an arithmetic task reflected levels of performance. Thirty participants (ages 18–24 years) performed a combination of tasks inducing both physical and mental workload. Type of physical effort, frequency of movement, and force exertion level were manipulated to alter the workload associated with the physical activity. Changes in subjective ratings generally corresponded to changes in both performance on the arithmetic task and objective mental workload assessment. Some discrepancies occurred at the highest physical force exertion level as participants perceived an increase in effort to maintain the same level of performance. Further research is needed to determine the force exertion threshold, beyond which the physical effort required interferes with mental workload and/or cognitive performance.

Relevance to industry: Technological advancements have increased the requirement for many workers to execute cognitive tasks concurrently with physical activity. When designing and evaluating such situations it is important to determine the interactive effects of these activities. A simple, uni-dimensional tool is suggested as a screening tool to identify situations requiring excessive or increased mental workload that many degrade performance or place additional stress on the individual.

1. Introduction

An assessment of mental workload is an important aspect in the design and evaluation of an occupational task. Efficient performance requires concentration on task-related information and suppression of extraneous stimuli to avoid information overload. Excessive levels of mental workload can cause errors or delayed information processing, particularly if the amount of information presented surpasses processing capacity (Ryu and Myung, 2005). Although the source of a considerable portion of the information obtained is directly related to a cognitive task, workers are often expected to perform physically demanding work concurrently, a situation that may require resource allotment. Examples include the public safety sector (e.g. police officers and firefighters), soldiers performing combat function, and occupations requiring extensive computer work. In such situations, there is a need to determine the impact that physical components may have on mental workload and to control factors that may increase the difficulty of tasks. Specifically, if considerable levels of both physical and mental activity are required, task (re)design might seek to avoid forms of physical activity that impair mental processing or decrease performance.

Past research in this area has focused predominantly on assessing the influence of physical demands on cognitive performance, but has yielded inconclusive results. Early work by Davey (1973) and Gupta et al. (1974) showed that cognitive performance increased immediately following low levels of physical activity, but that long-term exercise caused decrements in cognitive performance. More recent work supports the theory that physical workload increases the speed of information processing for simple cognitive tasks, such as detection, visual searches, and choice-responses (Eef Hogervorst et al., 1996; Tomporowski, 2003).

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However, concomitant physical activity may have dissimilar effects on complex cognitive tasks, including problem-solving and decision-making (Mozrall and Drury, 1996; Tomporowski, 2003). For example, Mastroianni et al. (2003) found no differences in the speed or accuracy of performance of mental arithmetic problems while hiking with loaded backpacks of different weights.

A body of evidence on assessing mental workload also exists regarding the utility of alternative measures to cognitive performance, including subjective (e.g., DiDomenico and Nussbaum, 2008; Pickup et al., 2005), physiological (e.g., Ahlstrom and Friedman-Berg, 2006; Ryu and Myung, 2005), and combined approaches (e.g., Jung and Jung, 2001; Miyake, 2001). While certain aspects of a mental task appear to have differential influences on mental workload indexes (Miyake, 1997), the effects of concurrent physical demands have not been fully investigated.

The extent to which different types of physical tasks affect performance and mental workload assessment has yet to be determined. In addition to inconsistent earlier results regarding the effects of physical demands on cognitive performance (as summarized above), existing evidence is also inconclusive as to the effects of physical demands on assessments of mental workload. While there are a number of assessment measures available that have been used extensively to assess mental workload (e.g. heart rate variability, eye movement and NASA Task Load Index), there has been little investigation of the validity of current assessment tools during situations that require concurrent physical and mental demands. Initial research using a single type of physical task indicated that individuals have a reasonable ability, using subjective assessments, to evaluate distinctly their levels of physical and mental workload during tasks involving concurrent mental and physical demands (DiDomenico and Nussbaum, 2008). The current experiment examined the effects of several distinct types of physical effort in the presence of a constant level of mental workload. The primary objective was to determine whether there was a differential effect of various types of physical activity on both mental workload and cognitive performance. It was hypothesized that physical activities that were more demanding (e.g., higher frequency, higher force exertions, or larger muscle groups) would lead to larger decrements in performance and higher levels of mental workload.

2. Methods

2.1. Participants

Thirty volunteers, between 18 and 24 years of age and with equal numbers of each gender, were recruited from the local community. Mean (SD) age and body mass of the participants were 20.2 (1.7) years and 71.2 (14.6) kg, respectively. A homogeneous age group was used to avoid potential age effects. In addition, all participants were university undergraduate students, reducing possible effects caused by differing educational backgrounds. All participants reported being in good health and having no history of musculoskeletal injuries within the prior year. All completed an informed consent procedure approved by the University's Institutional Review Board.

2.2. Experimental design and independent variables

A $3 \times 2 \times 3$, full factorial, repeated measures design was implemented with three independent variables: type of physical effort, frequency of movement, and force exertion level. Participants completed experimental trials in each of the 18 combinations, the order of which was randomly presented. Each trial involved performing a combination of tasks inducing both physical and mental workload.

Three types of physical effort were used, and intended to represent a variety of distinct fundamental movement types. Two of the tasks were "localized" (upper or lower limbs), while the third involved more "global" (whole-body) physical demands. The former required active elbow flexion or knee extension while seated on a commercial dynamometer (Biodex System 3 Pro, Biodex Medical Systems, Inc., Shirley, NY), throughout the full range of motion and using the (self-reported) dominant limbs. Whole-body exertions entailed lifting a load from the floor and carrying it while traversing up and down a set of three stairs (arranged as an inverted "V"). Stair height and depth were, respectively, 172 mm (7") and 270 mm (11"), consistent with architectural standards for indoor stairs (Hoke Jr., 1988). Loads were carried in wooden boxes (width = 600 mm, depth = 340 mm), with the appropriate mass (see below) achieved using small iron pieces placed in the box. Cutouts in the lateral faces served as handles.

Frequency of movements was controlled at two levels (low, high). Low frequency movements involved one extremity motion (elbow flexion or knee extension) every 10 s or one pass up and down the stairs every 30 s. High frequency movements were performed every 5 s for the extremities and every 12 s for stair climbing. These frequencies were chosen, based on pilot work, to allow for relatively continuous movement with brief rest breaks. Participants maintained a consistent pace by following computer-generated auditory tones.

Individuals performed the physical tasks at three force exertion levels: 8, 14, and 20% of their maximum voluntary ability. Normalized levels were used to account for individual differences in strength and to allow for inter-individual comparisons. These tasks were performed isotonically on a commercial dynamometer (Biodex System 3 Pro, Biodex Medical Systems, Inc., Shirley, NY), with resistances set to the noted percentages. Target angular velocities of 45 deg/sec for the elbow and 30 deg/sec for the knee were achieved using the auditory tones noted earlier, and the specific values were determined during pilot work as requiring moderate levels of physical demands and roughly representative of moderately-dynamic activities. Maximal ability was assessed prior to the experimental trials. Three maximum voluntary isokinetic contractions (MVICs) were performed in elbow flexion and knee extension at the same angular velocities as the experimental trials. The peak moment across replications was obtained, after accounting for gravitational effects, and the three force exertion levels were set as a percentage of this. Loads for the whole-body exertions (lifting and stair climbing) were determined as percentages of individual body mass.

The specific force exertion levels noted were identified during initial pilot work, in which the tasks were performed in the absence of any additional mental task. These levels were determined to be sufficiently distinct, as revealed by ratings of perceived exertions using Borg's CR10 scale (Borg, 1982). Note that the 20% level was not intended as a maximal workload level; rather, it was "relatively" high in relation to the other levels. Additional pilot work was undertaken to identify a trial duration that would meet two objectives; the trial should be long enough for physiological responses to reach steady state, yet short enough to avoid potentially confounding effects of fatigue. From obtained ratings of perceived exertion and measures of normalized heart rate, a 4-min duration was considered appropriate.

2.3. Experimental procedures

Participants completed trials involving the concurrent execution of a physical and mental task, each over a duration of 4 min. During each of the 18 physical task conditions, participants also completed arithmetic problems involving subtraction of two numbers (each between 21–99). A verbal arithmetic task was chosen to introduce substantial mental workload without creating structural interference with the physical tasks (Kahneman, 1973). Arithmetic tasks have been shown to be complex since recall, rehearsal, and cognitive processes are required to complete the operations (Kahneman, 1973; Luximon and Goonetilleke, 2001). Therefore, successful completion of the concurrent tasks required an alteration in allocation policy depending on the given parameters of the physical task.

Pairs of numbers were created using a random number generator and were continuously presented in a random order throughout a trial. Answers were verbalized to avoid structural interference with the physical task. Number pairs were repeated until a correct response was given. The subsequent pair of numbers was provided immediately following a correct response. The difficulty level of the arithmetic task was kept constant, and it was presumed to involve a moderate level of mental workload to perform the operation and rehearsal within short-term memory (Kahneman, 1973). Although neither the physical or mental tasks were indicated as being more important, it was emphasized to participants that maintaining the pace of the physical task was required and no time limit was specified for completing the arithmetic problems.

Performance during the mental task was determined as the number of correct responses provided in each condition. Clearly, the number of arithmetic problems completed correctly would be reduced due to incorrect responses and slower response times. The metric of the number of correct responses was chosen because the duration of the conditions was fixed and the presentation speed of the numbered pairs was dictated by the ability of the participant, thus reflecting the workload required.

At the conclusion of each trial, a rest period of at least 2 min was provided to minimize the development of physical or mental fatigue. During these breaks, subjective workload assessments of the immediately preceding trial were obtained as described below. The entire experiment took approximately 3 h per participant.

2.4. Mental workload assessment

Both an objective and a subjective measure were used to evaluate mental workload. The former was heart rate variability (HRV), which is commonly interpreted as a physiological representation of the reaction of the cardiovascular system to mental workload (Meshkati, 1988; Miyake, 2001). A heart rate monitor (Polar™ S810, Polar Electro Inc., Lake Success, NY) was used to record heart rate (HR); this was done continuously, beginning prior to and ending with the completion of each trial. Using the monitor (and software), each heartbeat and normal-to-normal (NN) interbeat intervals were identified. Resulting data were filtered to remove errors (Kemper et al., 2007). HR data were not captured for several trials conducted by one participant, thus all HR data for this participant were excluded from subsequent analyses. The standard deviation of all NN intervals (SDNN), as a measure of HRV, was determined over the last minute of each trial (Malik et al., 1996).

A visual analog (VA) scale was used to record participants' overall assessments of the mental workload necessary to complete each trial. The scale consisted of a 10 cm horizontal line with anchored endpoints of "no exertion at all" and "maximal exertion." Participants were instructed to indicate the magnitude of their perception by marking the scale appropriately (Price, 1994). Dependent measures, ranging from 0 to 100, were determined by measuring the distance from the lower anchor (i.e., 0 = no exertion). The VA Scale was used here because of its relative simplicity for determining an overall mental workload assessment score.

2.5. Analysis

Dependent measures consisted of mental workload indicators obtained from the VA scale and heart rate variability (SDNN) as well as the performance measure (# correct responses). Performance and SDNN were logarithmically transformed to obtain normally distributed residuals prior to subsequent analyses (summary results are presented in the original units). Univariate, repeated measures analyses of variance were performed to evaluate the effects of type of physical effort, frequency of movement, and load level on each of the dependent measures. Trial order was included as a blocking variable. Post hoc analyses, using the Tukey–Kramer HSD test and contrasts, were used where relevant. All statistical analyses were evaluated at a significance level of $\alpha = 0.05$, and all summary values are given as means (SD).

3. Results

3.1. Performance

Performance on the arithmetic task (Table 1) was affected by the type of effort ($p = 0.033$) and the frequency of movement ($p < 0.001$) but not by force exertion level ($p = 0.17$). The whole-body carry and knee extension conditions resulted in the same number of correct responses; however, there was a significant 5% reduction in correct responses during elbow flexion. The number of problems answered correctly during each trial was significantly reduced (by 6.5%) at the high frequency as compared to the low frequency condition. Though the interactive effect of type of effort and frequency was not significant ($p = 0.063$), the performance decrement at the higher frequency was larger in the elbow flexion and whole-body carry conditions. No other interactive effects were significant ($p > 0.132$).

3.2. Objective mental workload assessment

SDNN was significantly affected by type of effort ($p < 0.001$), frequency of movement ($p < 0.001$), and force exertion level ($p = 0.05$). Values for elbow flexion, knee extension, and the whole-body carry were 60.9 (21.7), 50.6 (21.7), and 38.1 (25.7) ms, respectively, and all pairwise differences among these were significant. SDNN was inversely related to frequency, being 44.2 (24.8) ms at the high frequency versus 55.5 (24.6) ms at the low frequency. Increasing the force exertion level led to decreases in SDNN. No pairwise differences between force exertion levels were significant, though the two higher force exertion levels as a group had significantly lower SDNN (by ∼8%) than the lowest load. There was a significant ($p < 0.001$) interactive effect of type of effort and frequency of movement on SDNN (Fig. 1), as evidenced by an increased influence of frequency in the global exertion (whole-

Table 1
Mean (s.d.) number of correct responses provided in the arithmetic task in each type of effort, force exertion level, and frequency of movement. Asterisks (*) indicate group designation based on statistically significant difference.

	Performance (# of correct responses)
Type of Effort	
Elbow Flexion	22.4 (8.1)*
Knee Extension	23.1 (8.5)**
Whole-body Carry	23.1 (7.6)**
Frequency of Movement	
Low	23.5 (8.2)*
High	22.3 (7.9)**
Force Exertion Level	
Low	22.9 (8.0)*
Medium	23.6 (8.3)*
High	22.2 (7.9)*

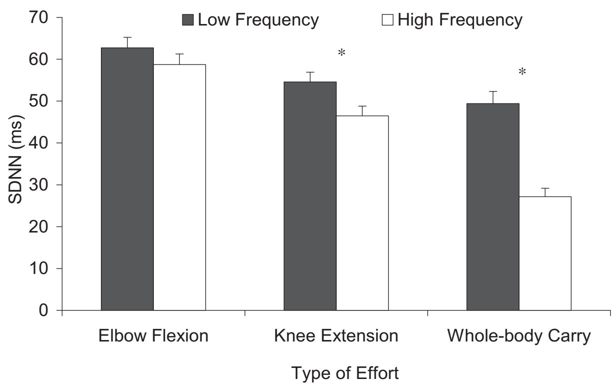

Fig. 1. Standard deviation of normal-to-normal intervals (SDNN) of HR during varying types of effort and frequencies. Vertical bars represent standard errors. The symbol * indicates a significant difference between frequencies.

body carry) as compared to the localized exertions (elbow flexion and knee extension). A significant ($p = 0.036$) interactive effect of type of effort and force exertion level was also found (Fig. 2). SDNN increased at the highest force exertion for elbow flexion, whereas a slight decrease in SDNN was associated with increases in force exertion during knee flexion and the whole-body carry. No other interactive effects were significant ($p > 0.37$).

3.3. *Subjective mental workload assessment*

Assessments of mental workload, using the VA scale (Table 2), were significantly affected by type of effort ($p = 0.001$), frequency of movement ($p < 0.001$), and force exertion level ($p < 0.001$). Responses during elbow flexion were the highest, at 47.7 (18.3), and significantly lower (by ~7%) during the other two tasks. Perceived mental workload was 43.8 (20.2) and 47.5 (19.4) in the low and high frequency conditions, respectively. VA scale ratings increased with increasing force exertion level. Responses to the lowest force exertion were smallest, at 43.2 (20.5), and significantly higher (by ~7%) for the other two force exertions. No interactive effects were significant ($p > 0.21$).

4. Discussion

During the evaluation (or design) of work systems it is important to assess (or control) aspects that may increase the difficulty of tasks or hinder execution. Of interest here were situations requiring considerable levels of both physical and mental activity. The ability to perform multiple tasks depends on the complexity of each task, with difficult or complex tasks demanding more effort than easy tasks. An evaluation of task demands by the individual controls the supply of capacity and arousal level (Kahneman, 1973). When activities require more mental effort than is available, the ability to perform the activities simultaneously is limited and performance degrades.

Table 2
Mean (s.d.) subjective mental workload ratings (visual analog scale, 0-100) in each type of effort, force exertion level, and frequency of movement. Asterisks (*) indicate group designation based on statistically significant difference.

	Subjective Workload Ratings (unitless)
Type of Effort	
Elbow Flexion	47.7 (18.3)*
Knee Extension	44.6 (20.6)**
Whole-body Carry	44.7 (20.6)**
Frequency of Movement	
Low	43.8 (20.2)*
High	47.5 (19.4)**
Force Exertion Level	
Low	43.2 (20.5)*
Medium	45.7 (19.2)**
High	48.0 (19.7)***

Effective measures of mental workload should be able to discriminate between mental workload produced by different types of tasks (diagnosticity) and different levels of difficulty (sensitivity). In the present study, localized (elbow flexion and knee extension) and global (whole-body carry) exertions were examined at different physical workloads that were achieved by varying frequencies and force exertion levels. The localized elbow flexion task caused a decrease in performance relative to the other two tasks even though the force exertion levels were comparable between types of effort (i.e., normalized to individual ability). Although the difference in correct responses was somewhat small (~5%), this was obtained during relatively short, 4-min trials. As such, cumulative decrements could be substantial over the course of a workday.

It is generally accepted that decreases in HRV (measured here using SDNN) reflect increases in mental workload when physical workload is negligible or consistent (Meshkati, 1988; Myrtek et al., 1999; Tattersall and Hockey, 1995). Since the arithmetic task involved (presumably) a relatively constant level of mental workload, the observed differences in SDNN responses may have

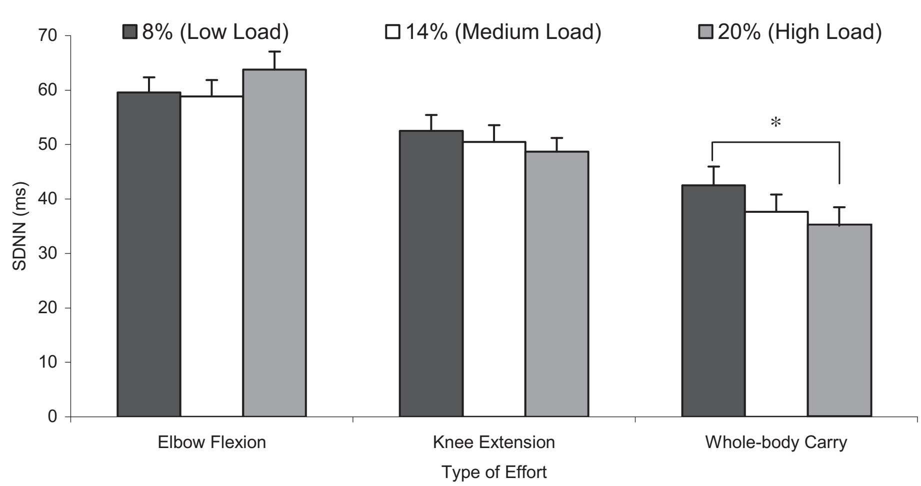

Fig. 2. Standard deviation of normal-to-normal intervals (SDNN) of HR during varying types of effort and loads. Load levels are percentages of maximum ability (as described in the Methods). Vertical bars represent standard errors. The symbol * indicates a significant difference between load levels.

resulted from one of two sources. SDNN decreased substantially when an increase in physical workload was required, either by increasing the frequency or requiring larger or more muscles to perform the physical task. It is thus plausible that the differences in HRV were due to changes in heart rate or respiration patterns that accompanied differing aerobic demands (Sammer, 1998). Indeed, physical task demands have been shown to induce changes in HRV during and immediately following intense exercise (Banach et al., 2004; Luft et al., 2009). Miyake's (1997) review of physiological measures indicated that HRV is a relatively consistent and reliable measure of mental workload when variations due to respiration are excluded. Although spectral analysis can be used in certain circumstances to exclude the effect of respirations, these analyses were not feasible in the current study.

It is also possible that the tasks under investigation differed in terms of inherent mental demands. For example, the whole-body carry clearly required a more substantial level of coordination, planning, and use of afferent feedback than did the two more localized efforts. As such, the observed differences in HRV may reflect these differences in required mental processing. Since the influence of physical workload on HRV within this study is undeterminable, it is unknown if the HRV levels were associated with levels of mental workload or a reflection of overall workload. Future work, perhaps using additional measures (e.g., respiration) or controlled level of aerobic demands, is needed to identify the relative contribution of these two influences on HRV.

Perceptions of mental workload corresponded closely to differences in arithmetic performance. For example, VA ratings were highest during elbow flexion and similar for knee extension and the whole-body carry, the same pattern (albeit inverted) as was found for performance. Also consistent between perceived mental workload and task performance was the lack of any significant interactive effects among the three manipulated aspects of the tasks (i.e., type of effort, frequency of movement, and force exertion level). Overall, these results suggest that perceived mental workload, obtained using a relatively simple tool (VA scale) is both sensitive (to induced mental workload) and specific (not substantially influenced by varying physical demands).

Performance on the arithmetic task was based on mental capabilities that likely varied substantially between individuals, so individuals with similar mental workload assessments may have had considerably different levels of performance. In the current study, participants rated mental workload as higher during conditions that degraded their performance on the mental arithmetic (e.g., during elbow flexion and at a higher frequency of movement). This concurs with previous evidence that perceptions of mental workload are sensitive to changes in the temporal demands of the tasks being performed (Rubio et al., 2004). Performance on the arithmetic task did not always deteriorate with an increase in mental workload. This result may simply be due to an individual, as a result of evaluating the difference between the demand and performance, investing more resources in order to meet demands (Yeh and Wickens, 1988). This likely occurred during the higher force exertion conditions; additional resources were invested to maintain the same level of performance, as reflected in the higher subjective ratings of mental workload.

Lower performance in the arithmetic task can be assumed to indicate an increase in mental workload. Hence, corresponding decreases in HRV were expected since the complexity of heart dynamics is related to the type of task and that the predictability of heart dynamics is related to the amount of load (Meshkati, 1988; Sammer, 1998). As task demands increase, physiological arousal mechanisms produce an increase in the available mental resources, resulting in physiological manifestations that indicate resource demand (Kahneman et al., 1973; Makowiec-Dabrowska et al., 1992; Meshkati, 1988). Here, HRV was influenced by movement frequency, force exertion level, and interactive effects of these factors with the type of effort. As suggested above, it remains unclear whether these differences in HRV reflect either differences in aerobic requirements and/or changes in overall mental workload. In contrast to the perceptual responses, HRV may be a less specific measure of mental workload, though perhaps more sensitive.

Within each type of effort, physical workload was altered by changing the frequency of the movement and the force exertion level. The increase in physical workload resulting from an increase in frequency was sufficient to degrade performance on the arithmetic task, decrease SDNN values during knee extension and the whole-body carry, and raise VA ratings. Although SDNN decreased during elbow flexion at the higher frequency, it was not significant. No significant changes in performance or SDNN accompanied changes to the force exertion. It is thus possible that the force exertion levels in the current study were not sufficiently large or diverse enough to accurately reflect the influence of force exertion on cognitive performance or HRV. DiDomenico and Nussbaum (2008) found that introducing a physical load reduced the number of correct responses provided during arithmetic tasks. Similar to the current study, performance generally degraded at the higher physical load levels. The minimal differences in HRV found here may be due to the fact that HRV is less reliable at lower workload levels and more sensitive to the increased workload associated with utilizing larger muscle groups. At higher levels of workload, interbeat intervals tend to be more constant over time, whereas at lower workload levels the frequency fluctuates (Meshkati, 1988; Nickel and Nachreiner, 2000).

In summary, the execution of a mental task with a concurrent physical task was altered by the magnitude of the physical demands required. Performing the physical tasks within this experiment required attentional resources and at times decreased cognitive performance, due in part to the tasks not being completely automatic, even for the highly controlled elbow flexion and knee extension. Using performance on the arithmetic task as an indicator of mental workload, individuals appeared to perceive changes in mental workload with moderate accuracy, as reflected in the VA ratings. Changes in VA ratings generally corresponded to both changes in performance on the arithmetic task and objective mental workload assessment using HRV. Some discrepancies occurred at the highest force exertion level as participants perceived an increase in effort to maintain the same level of performance. Similar to previous findings (DiDomenico and Nussbaum, 2008), lighter force exertions did not influence subjective mental workload assessments. Further research is needed to determine the force exertion threshold, beyond which the physical effort required interferes with subjective mental workload assessment. Results should also be verified for more novel and/or less constrained localized efforts, including less repetitious tasks at heavier loads.

5. Conclusions

Physical tasks can be comprised of many different dimensions. Altering the type of effort, frequency of movement, and force exertion levels affected the physical demands associated with the tasks. Individuals were more sensitive to changes in workload, manifested through an increase in effort, as compared to physiological changes and performance decrements. HRV seemed to have limitations when compared across different types of tasks, but within tasks the results provided were similar to the performance measure. Subjective measures may be useful in indicating potential performance problems if task demands are further increased (Yeh and Wickens, 1988), therefore, an uni-dimensional tool, such as the VA Scale, is suggested as a screening tool to identify situations requiring excessive or increased mental workload. Additional tools could be used to obtain more detailed and diagnostic information.

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