Published in final edited form as:
Motiv Emot. 2014 December 1; 38(6): 844–854. doi:10.1007/s11031-014-9433-2.

Assessment of Adult Age differences in Task Engagement: The Utility of Systolic Blood Pressure

Thomas M. Hess and
Department of Psychology, North Carolina State University, Raleigh, NC 27695-7650, 919-515-1729 (office), 919-515-1716 (fax)

Gilda E. Ennis
School of Psychology, Georgia Institute of Technology, Atlanta, GA 30332-0170

Thomas M. Hess: thomas_hess@ncsu.edu

Abstract

The constructs of effort and engagement are central to many theoretical frameworks associated with the study of aging. Age differences in the effort associated with effortful cognitive operations have been hypothesized to account for aging effects in ability, and shifting goals and motivation have been hypothesized to be associated with differential levels of engagement across situations in younger and older adults. Unfortunately, the assessment of effort and engagement—constructs that we view as relatively synonymous—has suffered in the field of aging due to the lack of well-validated measures. We suggest that systolic blood pressure might provide an easy and valid means for examining age differences in mental effort, and present evidence in support of its usage. Existing findings clearly support its potential utility, but further empirical and theoretical work is necessary.

Keywords

aging; motivation; effort; engagement; blood pressure

A major focus in the study of adult development is on determining the impact of aging on functioning in everyday life and the ability of older adults to maintain independence. A considerable amount of research addressing these issues has focused on cognitive ability, especially the nature of change in abilities thought to underlie functioning, the relationship between abilities and everyday functioning, and the factors that moderate cognitive decline or change. In spite of the logical assumption that cognitive ability should be predictive of everyday behavior, research has not established a clear relationship between the two (e.g., Allaire, 2012). In addition, in realms where ability would appear to form an important foundation for functioning, the relationships between age and performance are oftentimes minimal (e.g., job performance; McEvoy & Cascio, 1989; Schmidt & Hunter, 1998). As noted by Salthouse (2012), an important question then relates to why normative age-related

Correspondence should be addressed to Thomas M. Hess, Department of Psychology, North Carolina State University, Raleigh, NC 27695-7801. thomas_hess@ncsu.edu.

declines in cognitive ability—as assessed by standard cognitive tasks and ability measures—are not more consequential in terms of influencing everyday functioning.

One potential reason for this mismatch in expectations and reality may have to do with the failure to consider the role of motivation in determining performance. There is increasing evidence that motivational factors play an important role in determining age differences in performance, with these factors operating through goal-based selection processes. Age differences may occur with respect to the types of activities in which individuals choose to engage or, relatedly, the amount of effort that individuals exert in performing a given activity. This in turn may affect performance on a particular task and the observation of age differences therein. For example, the selection, optimization, and compensation model (Baltes, 1997) argues that aging is associated with changes in resources—broadly defined—which influence not only what one is capable of achieving, but also the effort required to achieve specific outcomes. This is hypothesized to result in an adjustment in the hierarchy of goals, resulting in a shift from a focus on growth in young adulthood to a focus on maintenance of functioning in later adulthood. Evidence consistent with this perspective can be seen both in self-reports of goal-orientations as well as differences in effort exerted by different-aged individuals based upon consistency of a given task with their goals (Freund & Ebner, 2005). For example, Freund (2006) found that older adults were more likely to engage cognitive resources in a task that was characterized as reflecting maintenance as opposed to improvement in functioning, whereas the opposite was true for younger adults.

We have argued that certain age differences in behavior may be reflective of even more basic processes having to do with relatively global goals associated with conservation of cognitive resources (Hess, 2006, in press; Hess & Emery, 2012). Such goals are most certainly operative across the lifespan, but specific factors associated with aging—most notably the increased costs of cognitive engagement—may increase their salience in later life as well as their role in determining age differences in functioning. We have conceptualized these costs in terms of the effort required to achieve a specific level of objective task performance, and resultant fatigue associated with the increased effort. The effects of these costs can be understood in terms of benefit/cost ratios (BCR) associated with specific tasks, which determine the probability of an individual engaging in the task. If the BCR exceeds an individual's threshold of engagement (i.e., the point at which perceived benefits sufficiently outweigh perceived costs), the probability of engagement will be high due to the belief that the task is worthwhile. Within this framework, we have argued that increasing costs in later life will have at least two effects.

First, normative increases in costs associated with aging will result in reduced BCRs at any given level of perceived benefit, resulting in an overall decrease in the range of activities exceeding the threshold of engagement. We have further hypothesized that this increase will be associated with a decline in the intrinsic motivation to engage in cognitively demanding tasks. Both will lead to a general decline in participation in such activities in everyday life. Second, the increased costs associated with performance in later life and the concomitant adjustment in BCRs associated with specific tasks will also result in the value placed on a task (e.g., self-relevance) being an increasingly important determinant of engagement through adulthood. That is, fewer tasks with low to moderate perceived benefits will exceed the threshold of engagement in older relative to younger adulthood. Thus, factors such as self-relevance become more important in determining engagement with increasing age, resulting in greater selectivity of resource engagement in later life based on task value.

The constructs of effort and engagement are central to these motivation-based perspectives. However, conceptualization and assessment of these two constructs in relation to aging has not kept pace with the development of these theoretical perspectives. For example, mental effort has often been used as a metaphor for cognitive resources in the aging literature (see Salthouse, 1988), with changes in the effort required to perform cognitively demanding tasks hypothesized to underlie age-related declines in performance (e.g., Craik, 1986). Unfortunately, the typical instantiation of this construct has not been clearly distinguished empirically from other conceptualizations of cognitive resources thought to underlie aging effects on performance, such as working memory or speed of processing (e.g., McCabe et al., 2010; Park & Payer, 2006; Salthouse, 1996). We contend, however, that mental effort is not synonymous with other resource constructs in that effort reflects energy expenditure and results in fatigue. We specifically define effort as energy investment (see Richter, 2013), a process that can result in fatigue as energy is exerted to obtain task success. Energy expenditure and fatigue effects are not clearly reflected in performance outcomes (e.g., working memory span) used to support other resource constructs, and thus require more valid means of assessment. Likewise, the means often used to assess resource engagement (e.g., time on task) in studies examining goal-based motivational processes do not necessarily result in a clear mapping onto the construct of engagement. We use the terms *effort* and *engagement* relatively interchangeably throughout this paper. This reflects our assumptions that engagement of cognitive resources requires the expenditure of mental effort, and that degree of effort expended is a measure of engagement. Given this definition, engagement is viewed as cognitively demanding, and thus is most accurately assessed by measures reflective of such demands. Thus, for example, even though the results of the aforementioned study by Freund (2006) seem to clearly support differences in resource engagement reflective of age-related goals, the use of a simple time-on-task measure in that study might lead to some questions regarding the interpretation of the results. Whereas increases in resource engagement are likely to be reflected in increases in the time that an individual spends performing a task, the converse is not true. Someone could spend a lot of time doing a task, but not engage much effort in support of performance.

As suggested by theories of cognitive energetics (see Tomporowski, 2008), we assume that mental effort is tied to physical costs and that—at some level—individuals monitor the effort associated with regulatory functions (e.g., achieving a specific goal state) in making decisions to engage or withdraw resources. Thus, the increased costs of cognitive activity in later life might be used to not only explain performance decrements associated with greater demands on cognitive resources, but also changes in motivational states associated with task engagement. This expands upon previous views of cognitive aging by proposing a relatively novel, but potentially powerful conceptual framework that ties changes in performance, motivation, and engagement to the same underlying mechanisms: the costs associated with engaging cognitive resources. This perspective, along with the increased focus on motivational processes in adulthood, make it clear that the study of aging would benefit from the identification of measures of effort and engagement that would not only be valid and reliable in older adults, but also permit comparisons across age groups.

The Costs of Cognitive Activity

In examining the literature on aging, several lines of research have obtained findings suggestive of an increase in the costs associated with effortful cognitive activity in later life. At the behavioral level, older adults are disproportionately affected by cognitive load relative to younger adults, and their performance suffers more under dual-task conditions (Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). Research also suggests that declines in sensory systems increase the effort associated with registration of information in old age, which in turn has a negative effect on subsequent task performance (e.g., Murphy, Craik, Li, & Schneider, 2000; Tun, McCoy, & Wingfield, 2009). Older adults' subjective ratings of effort in vigilance tasks also increase more than those of younger adults over time, even in the absence of age differences in performance (Bunce & Sisa, 2002; Deaton & Parasuraman, 1993). This suggests that the sustained engagement of cognitive resources in support of a specific objective level of performance is more consequential in later life. Examining the subjective perceptions of costs, Westbrook, Kester, and Braver (2013) provided related results. Using a discounting procedure, they found that older adults viewed cognitive activity as more costly than did younger adults.

Although these behavioral findings are in line with expectations, their relation to more direct expressions of costs at the physiological level is not clear. There are some physiological data that are informative with respect to age differences in costs. For example, studies have shown that older adults exhibit stronger cortisol responses following a cognitive challenge than do younger adults (e.g., Neupert, Soederberg, & Lachman, 2006; Steptoe, Kunz-Ebrecht, Wright, & Feldman, 2005), and also take longer to recover from such stress-related responses (e.g., Seeman & Robbins, 1994). Reviewing research from both the animal and human literature, Gold (2005) concluded that glucose utilization in the brain during effortful cognitive activity is less efficient in later life, as is replenishment of cortical glucose reserves.

Taken together, these findings suggest that the physiological mechanisms supporting cognitive activity may be generally less efficient, and that recovery from such activity (i.e., depletion effects) takes longer in later adulthood. Unfortunately, research in this area has not systematically studied age differences in responses as a function of important factors such as task difficulty or personal goals. One potentially informative avenue of research can be found in neuroimaging studies. Specifically, some evidence suggests that older adults have to engage more resources to achieve the same levels of performance as younger adults (for reviews, see Cabeza, 2002; Park & Reuter-Lorenz, 2009). Whereas this more widespread cortical recruitment in older adults to achieve comparable levels of performance to young adults is often viewed as compensatory, we suggest that this is reflective of the increased cost of cognitive activity in later life. For example, Cappell et al. (2010) found that older adults recruited similar cortical resources as younger adults in a working memory task, but they did so at lower levels of task difficulty (e.g., the shift in activation levels from memory load of 4 to 5 was similar to that observed with younger adults moving from loads of 5 to 7).

Although this over-recruitment may be compensatory, the commonality in underlying process across age groups as difficulty increased seems inconsistent with definitions characterizing compensation as dealing with deficits via alternative means to support performance (Bäckman & Dixon, 1992). We suggest, instead, that this pattern of age differences reflects the increased costs associated with achieving an objective level of performance in later life rather than a qualitative shift in processing: older adults were using similar resources to those used by the young, but at a lower level of task difficulty.

Although the neuroimaging findings are consistent with a perspective of increasing costs of cognitive activity in old age, interpretation of these effects suffers from the lack of a clear conceptual foundation for it. Other measures thought to more clearly reflect effort or task engagement have been used in some studies of aging, but many of these suffer due to other aging-related processes that affect comparability across age groups. For example, pupil size is associated with mental effort in a variety of contexts (for review, see Beatty, 1982), and several studies have used this measure successfully with older adults, observing changes in pupil size that were meaningfully related to task demands (e.g., Kim, Beversdorf, & Heilman, 2000; Kuchinsky et al., 2013; Piquado, Isaacowitz, & Wingfield, 2010; Van Gerven, Paas, Van Merriënboer, & Schmidt, 2004). A concern with this measure, however, relates to normative reductions in both pupil size and range of response in later life. Thus, whereas this measure can be meaningfully used to assess effort and engagement within age groups, aging-related changes in the characteristics of the eye make it difficult to make between-age comparisons.

The assessment of effort

Cardiovascular response

One potential index of engagement that may prove useful in examining aging effects involves cardiovascular (CV) responses, with a particular focus on systolic blood pressure (SBP). Based on extensions of Obrist's (1981) active coping model with Brehm's motivational intensity theory (Brehm & Self, 1989), a coherent body of research suggests that SBP response (i.e., change in SBP from a resting state) is a potentially promising measure of mental effort (e.g., Gendolla & Richter, 2006; Gendolla, Richter, & Silvia, 2008; Wright & Dill, 1993; Wright, Martin & Bland, 2003; Wright et al., 2007). According to Obrist (1981), active coping occurs when action, whether overt or covert, is perceived as necessary to cope effectively with a situation. Action taken during coping evokes sympathetic nervous system excitation of the heart, resulting in an increase in the force of myocardial contraction. SBP, which is a measure of peak arterial pressure during myocardial contraction (i.e. the period of systole in the cardiac cycle), is influenced by sympathetically induced elevations of myocardial contractile force (Guyton, 1991; Vick, 1984); thus, the SBP response can reflect sympathetic (β-adrenergic) activity upon the myocardium. Relative to SBP, other standard measures of CV responsivity, such as heart rate (HR) and diastolic blood pressure (DBP), are less reflective of sympathetic activation of the heart (Richter, Friedrich, & Gendolla, 2008). HR, which is a measure of the frequency of cardiac contractions per minute, does increase under sympathetic influence, but parasympathetic dominance makes it a less sensitive measure (Berntson, Quigley, & Lozano, 2007). Because

DBP is a measure of arterial pressure during diastole—the period of cardiac relaxation in the cardiac cycle—it is less influenced by myocardial contraction than SBP. DBP is determined primarily by peripheral vascular resistance (PVR) (or the resistance to blood flow throughout the systemic vasculature), which may either increase during a sympathetic response due to vasoconstriction, not change significantly due to the countervailing influence of vasodilation, or decrease due to increased vasodilation, especially following maximal exercise (Guyton, 1991; Piepoli et al., 1993; Wright & Kirby, 2001). Thus, among the standard measures of CV responsivity, SBP response provides a more accurate index of the degree of active coping, and in the framework of motivational intensity theory, it provides a valid means for assessing effort or the mobilization of energy resources to meet situational demands (Richter, 2013).

Wright's (1996) integration of Obrist's (1981) active coping model with Brehm's motivational intensity theory (Brehm & Self, 1989) suggests that sympathetic nervous system influence upon the heart, and subsequent elevation of SBP, will increase during a challenge depending upon the amount of effort exerted, an elevation that is dependent upon the level of task difficulty and the degree that task success is perceived as possible and worthwhile (e.g. Wright et al., 2007). People who engage in a difficult task will exert more effort than people who engage in an easy task, as long as both have similar abilities and perceive task success as possible and worthwhile. Further, the amount of effort exerted in an initial task will influence the amount of effort invested to complete subsequent tasks, such that those who exert greater effort in an initial task will have to invest even more effort in a subsequent task to achieve success. When task demands are high, people will be more likely to disengage, or withdraw effort, because success may seem improbable or not worthwhile (i.e., the cost of success may seem too high).

Support for these assertions comes from studies of young adults by Wright and colleagues (Wright & Dill, 1993; Wright, Dill, Geen, & Anderson, 1998; Wright et al., 2007, Experiment 1). During an initial work period, participants who engaged in a difficult task demonstrated a greater SBP response compared to those who worked on an easy task. Further, the SBP response of difficult-task participants remained higher in a subsequent task relative to the easy-task participants (Wright et al., 2007, Experiment 1). Assuming that both groups perceived that task success was probable and worthwhile, this suggests that initial high-demanding tasks cause fatigue requiring additional effort for the completion of later tasks. When task demands were high, disengagement occurred, a process found to be dependent upon perceived ability (Wright & Dill, 1993; Wright et al., 1998). During an easy task, participants with low perceived ability worked harder than participants with high perceived ability and then withdrew effort when task difficulty was high (Wright & Dill, 1993). To the extent that perceived ability overlaps with actual ability, those with low relative to high ability must exert more effort to obtain a similar objective level of performance and may disengage when task demands are increased, perhaps because task success seems improbable or the costs of engagement seem too high.

Other work integrating the active coping model with motivational intensity theory lends further support to the linkage between SBP response and situational and individual-differences factors associated with task difficulty and motivation (e.g., Gendolla & Richter, 2005, 2006; Wright, Dill, Geen, & Anderson, 1998; Wright et al., 2007). For example, SBP response is higher and increases in conditions of high versus low ego involvement (Gendolla & Wright, 2005), and is increased in conditions of social evaluation/observation versus no evaluation/observation (Gendolla & Richter, 2006; Wright et al., 1998). Wright and colleagues also found SBP response in an initial task is inversely related to SBP response in a cognitively demanding subsequent task (Wright et al., 2003; Wright et al., 2007, Experiment 2), indicating that sustained levels of difficult cognitive activity result in depletion of cognitive resources and energy.

Aging-related considerations

The promising nature of SBP as a measure of engagement in studies of aging relates to several factors. First, it does not show the same limitations in range of response as some other physiological measures, such as pupil size, HR, and skin conductance. Second, a recent meta-analysis (Uchino, Birmingham, & Berg, 2010) demonstrated that SBP was similarly sensitive to—what the authors termed—emotionally evocative stimulus conditions[1] across adult age groups. And third—as already mentioned—strong theoretical and empirical bases exist supporting the validity of SBP response as a measure of effort expenditure and task engagement. Although other approaches demonstrate some promise for studies of age differences, such as examinations of differential recruitment of cortical responses, they suffer from a lack of a strong, empirically validated framework regarding the relationship of response to engagement.

Although the range of response is less variable across age groups, a potential drawback of SBP with respect to examining age differences in engagement relates to the fact that Uchino et al. (2010) also found that older adults demonstrate stronger reactivity than do younger adults to emotionally evocative stimulus conditions. This age difference in reactivity increased with overall reactivity, suggesting that tasks evoking more coping resources resulted in stronger age differences. Uchino et al. interpreted this as reflecting a general decline in self-regulatory functions, which is more evident under more demanding conditions. Age differences in general reactivity may be problematic to the extent that they represent processes or mechanisms that are extraneous to those of interest, introducing potential measurement error. It is possible, however, that such error could be controlled in studies of engagement by partialling out general reactivity from task-specific reactivity. It may also be the case, however, that such reactivity is a manifestation of the same basic mechanisms typically associated with SBP responses to active coping. For example, if self-regulation skills in response to stressful situations decline with age, the resultant greater reactivity may reflect an uncontrolled or unfocused response that may be more or less automatically elicited by the situation. Although not reflecting controlled cognitive operations, it may reflect engagement and inefficient use of resources. Within our conceptual scheme, such reactivity may increase the hypothesized selectivity that we assume to occur in later life.

[1]In this analysis, emotionally evocative referred to a broad category of tasks defined as involving some form of active (e.g., math problems) or passive (e.g., cold pressor task) coping response. No age differences were observed, however, relating to the nature of coping.

As with most physiological functions, the cardiovascular system experiences changes over adulthood. Thus, consideration of the utility of SBP as a measure of engagement must be examined within this context. Specifically, does SBP respond in a qualitatively similar manner in young and older adulthood (e.g., exhibit increases as an individual deals with increasingly more difficult cognitive tasks) and, if so, are the mechanisms accounting for such change similar across age groups?

Adult age differences in SBP response during exercise and mental challenge have been assessed in a number of studies (Rodeheffer et al., 1984; Taylor, Hand, Johnson, & Seals, 1991; Uchino et al., 2010). While the resting level of SBP is greater in older than in younger adults, primarily due to stiffness or lack of compliance of the aorta and large arteries (Folkow & Svanborg, 1993; Pinto, 2007), research has found that SBP responsivity during exercise is similar in young and older adults who do not have coronary artery disease (Rodeheffer et al., 1984; Taylor et al., 1991). The SBP response is influenced by PVR and cardiac output (CO) (i.e., the amount of blood pumped by the heart per minute) (Pinto, 2007; Vick, 1984). Several studies have reported no significant age group differences in SBP during moderate or vigorous exercise, a result likely due to age-related similarities in elevations of PVR and CO (Rodeheffer et al., 1984; Taylor et al., 1991). The physiological mechanism responsible for the CO response in older adults is somewhat different from that in younger adults, however (Docherty, 1990; Lakatta, 1993). CO is determined by HR and stroke volume (i.e., the amount of blood pumped by the left ventricle in one contraction) (Vick, 1984). Sympathetically induced increases in myocardial contractile force can increase SV, potentially resulting in increased CO depending upon the degree of increase in SV and HR (Vick, 1984). Relative to young adults, the HR of older adults is attenuated due to decreased responsiveness to β-adrenergic stimuli (Ferrari, Radaelli, Centola, 2003). Thus, for CO to be maintained at levels similar to young adults during exercise, SV is increased (Docherty, 1990; Lakatta, 1993; Roedeheffer et al., 1984; Vick, 1984). Because older adults have a decreased heart rate response, the volume of blood remaining in the left ventricle at the end of diastole is greater relative to young adults. This age-related increase in end-diastolic volume stretches cardiac muscle, increasing the force of cardiac contraction resulting in elevated stroke volume, a process referred to as the Frank-Starling mechanism (Docherty, 1990; Guyton, 1991; Ferrari et al., 2003; Lakatta, 1993; Roedeheffer et al., 1984). Therefore, healthy older adults are able to maintain CO at levels similar to young adults, and can meet the energy demands of physical exercise. Age differences in CO responses, however, do emerge during maximal aerobic and prolonged exercise, so comparability of response only occurs up to a certain limit (Correia et al., 2002; Fleg et al., 1995).

Although the mechanisms underpinning the SBP response differ somewhat according to age, the SBP response to moderate physical exertion seems to increase by a similar degree across age groups. In conjunction with the findings of Wright and colleagues regarding the use of SBP response as a proxy for mental effort in young adults (Wright, 1996; Wright et al., 2003; Wright et al., 2007), these previously discussed findings from the cardiovascular physiology literature suggest that the SBP response can be reliably used to compare effort exerted during cognitive challenge in both young and older adults.

Age differences in engagement

Relatively little research has used SBP or other CV indices to assess age differences in mental effort, with most previous research using CV reactivity as a measure of emotional responses to stress and not of engagement. There have been, however, a few studies that examined reactivity to cognitively demanding tasks. For example, consistent with the current perspective, Jennings, Nebes, and Yovetich (1990) found that increasing the processing demands associated with a memory span task (adding a secondary task) resulted in a disproportionate increase in CV responses in older relative to younger adults. Other studies by these same researchers (Jennings, Brock, & Nebes, 1990; Jennings, Nebes, & Brock, 1988) found that age differences in CV responses were consistent with a perspective of aging being associated with an increase in the energetic demands of cognition. Steptoe, Moses, and Edwards (1990) also found that SBP responses increased with age and task demands—comparing easy vs. hard versions of the Raven's Progressive Matrices—and there was a trend toward demands having a greater impact with increasing age. Unfortunately, the oldest participants in this study were only 60 years old, thereby limiting generalizations to old age.

Several other studies have found an increase in SBP in response to cognitive performance in later adulthood (e.g., Boutcher & Stocker, 1996; Carroll et al., 2000; Hogan et al., 2012; Schapkin, Freude, Gajewski, Wild-Wall, & Falkenstein, 2012; Steptoe et al., 2005; Uchino et al., 1999). As noted earlier, a meta-analysis by Uchino et al. (2010) also found that age differences in SBP reactivity increased with level of mean reactivity, suggesting that as task demands increase—as reflected in indices of active coping—so do age differences in SBP response. Unfortunately, there have been relatively few studies examining age differences in responses to systematic changes in task demands.

We have recently conducted three studies in our lab in which we used ideas drawn from Wright (1996) and related perspectives to conduct empirical tests of our selective engagement framework (Hess, in press). SBP and other standard CV measures (DBP and HR) were assessed in each study using the Finometer MIDI (Finapres Medical Systems, Amsterdam, the Netherlands), a system that measures finger arterial pressure using the volume-clamp method of Peñáz (1973). Using SBP response (SBP-R; change from baseline) as a reflection of sympathetic nervous system activation, we were interested in testing the specific hypotheses that, relative to younger adults, older adults would require higher levels of effort to achieve a specific objective level of performance and experience greater fatigue due to the increased effort requirements associated with performance. We were also interested in testing specific hypotheses relating to motivational factors. First, we expected that the increased costs (i.e., greater effort and fatigue) associated with cognitive engagement in later life would also be associated with reduced levels of intrinsic motivation to engage in effortful cognitive activity. Second, we hypothesized that the higher levels of effort associated with performance would result in older adults disengaging from tasks at lower levels of objective difficulty relative to younger adults. And third, consistent with the idea that older adults are more selective in how they engage their resources, we predicted that variations in SBP-R associated with indices of motivation would be greater in older than in younger adults.

Note that in all of our studies, all participants—even young adults—were recruited from the community. As a precautionary measure, we excluded individuals from participation at recruitment if they had self-reported high blood pressure (i.e., SBP ≥ 160 mmHg or DBP ≥ 100 mmHg). We also excluded individuals at testing if their readings during screening or baseline exceeded these levels.

Our first study (Hess & Ennis, 2012) tested young (ages 19 – 45) and older (ages 62 – 84) adults using a procedure similar to that of Wright et al. (2007) to examine age differences in both effort associated with different levels of task difficulty and subsequent depletion effects. Specifically, participants engaged in either a relatively easy (counting forward by 1s) or difficult (counting backwards by 3s) task for 5 minutes, and then performed a moderately difficult task (a series of simple multiplication problems) for 3 minutes. CV responses (SBP, DBP, and HR) were recorded continuously for the duration of each task. Consistent with expectations, SBP-R was greater for older relative to younger adults at each level of difficulty for the initial task, and the age difference increased with level of difficulty. Fatigue effects were assessed by examining performance in the second task relative to that in the first task. Replicating past findings (e.g., Wright et al., 2003; Wright et al., 2007), SBP-R during the second task was higher following the difficult task than after the easier task. This can be viewed as analogous to what happens when one engages in physical activity where one task follows another. After muscles become fatigued during the initial physical task, individuals engaging in a subsequent task have to work harder than they would have if they had not engaged in the initial activity. The increase in SBP-R in the second task reflects the depletion of those resources needed to engage in a cognitive challenge. We also found that SBP-R was greater for older than for younger adults, suggesting greater depletion with increasing age. In addition, consistent with our hypothesis, this age difference in depletion was wholly accounted for by the amount of effort exerted during the initial task. Another interesting finding was that the high level of effort expended by older adults following the difficult task also appeared to have a disruptive effect on performance in the second task. This result appears consistent with theoretical perspectives arguing that declines in cognitive resources in later life result in high levels of arousal being more detrimental to older than to younger adults’ performance (e.g., Labouvie-Vief, 2009).

Our second study (Ennis, Hess, & Smith, 2013) examined age differences in SBP-R in relationship to systematic changes in task demands. Young (ages 20 – 40) and older (ages 64 – 85) adults were given a memory search task, with blocks of trials containing memory sets of 2 to 10 items. Once again, we found that older adults exhibited higher levels of SBP-R at each level of task difficulty (i.e., memory-set size), with the age difference generally increasing with task demands. Consistent with expectations, we also observed SBP-R to decrease at high levels of difficulty, which has been taken to represent the withdrawal of effort as task demands exceed judgment of ability or the extent to which continued exertion are consistent with the value the individual places on the task. Importantly, we found that the point at which the older adults as a group exhibited a significant downturn in SBP-R was at a lower level of task difficulty than the point at which younger adults did. This suggests that the age-related increase in the effort required to perform at a specific level of task difficulty resulted in older adults exceeding the threshold for disengagement (i.e., the effort required to perform the task exceeds the benefits of continued engagement) at an earlier point relative to younger adults.

We also assessed subjective reports of difficulty across levels of objective task difficulty. We observed that that these ratings increased with memory-set size, and were also greater in older than in younger adults. In addition, when these ratings were substituted for objective task difficulty in our analyses, we found that they were significant predictors of SBP-R, with age moderating this effect in a similar fashion to that observed in our initial analysis. This provided some support for the notion that individuals are aware—at some level—of the costs associated with cognitive activity, and that these ratings map onto more objective indices of age differences in costs (i.e., SBP-R).

Two other interesting age-related motivation effects were also observed. First, self-reported motivation to do well was positively associated with SBP-R, lending validity to the use of this measure as an index of task engagement. In addition, the impact of self-reported motivation was disproportionately stronger for older adults. This is consistent with expectations drawn from the selective engagement framework (Hess, in press), which argues that the increased costs associated with cognitive activity in later life leads to increased sensitivity to the self-related implications of the task. This results in older adults exhibiting greater selectivity in resource engagement and a closer linkage between behavior and motivational factors when compared to younger adults. Second, intrinsic motivation to seek out and engage in effortful cognitive activity—as assessed by Need for Cognition (Cacioppo, Petty, Feinstein, & Jarvis, 1996)—was also associated with engagement. Somewhat counterintuitively, however, those who were low in this need exhibited higher levels of engagement, with this effect once more being disproportionately larger in older adults. This finding can be viewed as consistent with another aspect of the selective engagement framework, however, which argues that age-related increases in the effort associated with cognitive activity lead to reductions in the intrinsic motivation to engage in such activity (Hess, in press). Given that this age-moderated effect was observed while controlling for other confounding factors (e.g., self-reported engagement, task performance), we interpreted it as reflective of the relation between the effort required to support performance and intrinsic motivation. As the effort required to support cognitive performance increases, the need to engage in effortful cognitive activity may decrease. Obviously, the cross-sectional nature of these data requires caution in making such an interpretation, but a similar effect has been observed in a longitudinal study examining the relationship between resources, intrinsic motivation, and activity engagement (Hess, Emery, & Neupert, 2011).

Another study using a memory search task obtained similar motivational effects (Smith & Hess, 2014). In this study, young (ages 18 – 35) and older (ages 65 – 85) adults performed the task at moderate levels of difficulty (i.e., memory sets of 2 – 6 letters) that essentially ensured high levels of performance so that the impact of task demands could be more systematically examined independent of disengagement effects that presumably would be most likely under very high levels of difficulty. Of primary interest was the impact of a manipulation designed to influence motivation to engage in the task. Specifically, participants were either given standard task instructions or informed that the experimenter would review their performance with them at the end of each trial block. Accountability manipulations have been found to increase engagement by heightening self-presentation concerns (see Lerner & Tetlock, 1999), and several studies have found that such instructions have a stronger effect on task performance in older than in younger adults (e.g., Hess, Germain, Swaim, & Osowski, 2009; Hess, Rosenberg, & Waters, 2001). Consistent with expectations, participants in the high accountability condition exhibited higher levels of SBP-R than did those in the low accountability condition, with the impact of accountability being greater in the old than in the young group. In addition to demonstrating that SBP-R is meaningfully associated with task engagement in studies of aging, this finding also supported our contention that the impact of accountability on performance—an imperfect measure of effort expenditure—was a reflection of engagement of cognitive resources.

This set of studies provides evidence for the utility of using SBP to assess adult age differences in effort expenditure. The fact that we obtained results that were systematically related to task demands and motivational factors, and that the obtained effects are consistent with expectations derived from several theoretical frameworks (e.g., Brehm & Self, 1989; Hess, 2013; Wright, 1996) also supports the validity of SBP as a measure of engagement across the age-span in adulthood. Several other findings from these studies lend further evidence that the obtained age effects are not reflections of other processes. First, all analyses in these studies used baseline SBP as a covariate, thereby controlling for the possibility that the obtained age effects do not simply reflect covariation of SBP-R with baseline levels. Second, both young and older participants in these studies reported low levels of stress, evaluation concerns, and threat associated with the testing context, thereby reducing the probability that these alternative mechanisms could account for the results. Finally, we also found that SBP responses in older adults were unaffected by hypertension medication.

Conclusions

This paper has focused on the role and assessment of mental effort in empirical and theoretical work in the field of aging. We have argued that, given the central role that the construct of effort has played in explaining age differences in cognitive functioning and the emerging focus on motivational factors in the field, greater attention needs to be paid to the assessment of effort and its utility in examining age differences across various contexts. The study of aging suffers from the same problems as any study of development, with measurement equivalence and construct validity being central to age-based comparisons. Thus, many measures that have been used successfully with younger adults may be problematic when extended into later life. This may be especially true when making comparisons between age groups.

We have attempted to build a case for the use of SBP as an effective tool in the study of aging. There are many aspects of this measure that are attractive in this regard, including similar reactivity to that observed in younger adults to conditions that vary in coping demands as well as maintained range of response. Although systematic investigations using SBP in the aging literature are scarce, recent empirical support for its use comes from studies demonstrating systematic relationships to variables relating to motivation and task difficulty. Certainly, challenges still exist in terms of ruling out alternative explanations for the obtained results (e.g., age differences in stress reactions) and validating patterns of SBP responses across age groups to other measures of costs of cognitive activity (e.g., subjective perceptions). However, we believe that the existing research is promising and supportive of further explorations using this measure.

Acknowledgments

Writing of this article was supported by NIA grants R01 AG05552, R01 AG020153, and R01 AG034580. Formulation of ideas presented here has been enhanced and enriched by the efforts of past and present members of the Adult Development Laboratory at North Carolina State University.

References

Allaire, JC. Everyday cognition. In: Whitbourne, SK.; Sliwinski, MJ., editors. The Wiley-Blackwell handbook of adulthood and aging. Hoboken, NJ: Wiley-Blackwell; 2012. p. 190-207.

Baltes PB. On the incomplete architecture of human ontogeny: Selection, optimization, and compensation as foundation of developmental theory. American Psychologist. 1997; 52:366–380. [PubMed: 9109347]

Beatty J. Task-evoked pupillary responses, processing load, and the structure of processing resources. Psychological Bulletin. 1982; 91:276–292.10.1037/0033-2909.91.2.276 [PubMed: 7071262]

Berntson, GG.; Quigley, KS.; Lozano, D. Cardiovascular psychophysiology. In: Cacioppo, JT.; Tassinary, LG.; Berntson, GG., editors. Handbook of psychophysiology. 3. Cambridge, UK: Cambridge University Press; 2007. p. 182-210.

Bäckman L, Dixon RA. Psychological compensation: A theoretical framework. Psychological Bulletin. 1992; 112:259–283.10.1037/0033-2909.112.2.259 [PubMed: 1454895]

Boutcher SH, Stocker D. Cardiovascular response of young and older males to mental challenge. The Journals of Gerontology: Series B: Psychological Sciences and Social Sciences. 1996; 51:261–267.10.1093/geronb/51B.5.P261

Brehm JW, Self EA. The intensity of motivation. Annual Review of Psychology. 1989; 40:109–131.10.1146/annurev.psych.40.1.109

Bunce D, Sisa L. Age differences in perceived workload across a short vigil. Ergonomics. 2002; 45:949–960.10.1080/00140130210166483 [PubMed: 12519526]

Cabeza R. Hemispheric asymmetry reduction in older adults: The HAROLD model. Psychology and Aging. 2002; 17:85–100.10.1037/0882-7974.17.1.85 [PubMed: 11931290]

Cacioppo JT, Petty RE, Feinstein JA, Jarvis WBG. Dispositional differences in cognitive motivation: The life and times of individuals varying in need for cognition. Psychological Bulletin. 1996; 119:197–253.10.1037//0033-2909.119.2.197

Cappell KA, Gmeindl L, Reuter-Lorenz PA. Age differences in prefontal recruitment during verbal working memory maintenance depend on memory load. Cortex: A Journal Devoted to the Study of the Nervous System and Behavior. 2010; 46:462–473.10.1016/j.cortex.2009.11.009 [PubMed: 20097332]

Craik, FI. A functional account of age differences in memory. In: Klix, F.; Hagendorf, H., editors. Human memory and cognitive capabilities, mechanisms, and performances. Amsterdam: Elsevier; 1986. p. 409-422.

Correia LCL, Lakatta EG, O'Connor FC, Becker LC, Clulow J, Townsend S, Fleg JL. Attenuated cardiovascular reserve during prolonged submaximal cycle exercise in healthy older subjects. Journal of the American College of Cardiology. 2002; 40:1290–1297. [PubMed: 12383577]

Deaton JE, Parasuraman R. Sensory and cognitive vigilance: Effects of age on performance and subjective workload. Human Performance. 1993; 6(1):71–97.10.1207/s15327043hup0601

Docherty JR. Cardiovascular responses in ageing: A review. Pharmacological Reviews. 1990; 42:103–125. [PubMed: 2198604]

Ennis GE, Hess TM, Smith BT. The Impact of age and motivation on cognitive effort: Implications for cognitive engagement in older adulthood. Psychology and Aging. 2013; 28:495–504.10.1037/a0031255 [PubMed: 23421325]

Ferrari AU, Radaelli A, Centola M. Invited Review: Aging and the cardiovascular system. Journal of Applied Physiology. 2003; 95:2591–2597.10.1152/japplphysiol.00601.2003 [PubMed: 14600164]

Fleg JL, O'Connor F, Gerstenblith G, Becker LC, Clulow J, Schulman SP, Lakatta EG. Impact of age on the cardiovascular response to dynamic upright exercise in healthy men and women. Journal of Applied Physiology. 1995; 78:890–900. [PubMed: 7775334]

Folkow B, Svanborg A. Physiology of cardiovascular aging. Physiological Reviews. 1993; 73:725–764. [PubMed: 8105498]

Freund AM. Age-differential motivational consequences of optimization versus compensation focus in younger and older adults. Psychology and Aging. 2006; 21:240–252.10.1037/0882-7974.21.2.240 [PubMed: 16768572]

Freund, AM.; Ebner, NC. The aging self: Shifting from promoting gains to balancing losses. In: Greve, W.; Rothermund, K.; Wentura, D., editors. The adaptive self: Personal continuity and intentional self-development. Ashland, OH: Hogrefe & Huber Publishers; 2005. p. 185-202.

Gendolla GH, Richter M. Ego involvement and effort: Cardiovascular, electrodermal, and performance effects. Psychophysiology. 2005; 42:595–603. [PubMed: 16176382]

Gendolla GHE, Richter M. Cardiovascular reactivity during performance under social observation: The moderating role of task difficulty. International Journal of Psychophysiology. 2006; 62:185–192.10.1016/j.ijpsycho.2006.04.002 [PubMed: 16750583]

Gendolla GHE, Richter M, Silvia PJ. Self-focus and task difficulty effects on effort-related cardiovascular reactivity. Psychophysiology. 2008; 45:653–662.10.1111/j.1469-8986.2008.00655.x [PubMed: 18282201]

Gendolla, GHE.; Wright, RA. Motivation in social settings: Studies of effort-related cardiovascular arousal. In: Forgas, JP.; Williams, K.; von Hippel, B., editors. Social motivation: Conscious and nonconscious processes. Cambridge University Press; 2005.

Gold PE. Glucose and age-related changes in memory. Neurobiology of Aging. 2005; 26S:S60–S64.

Guyton, AC. Textbook of medical physiology. Philadelphia: W.B. Saunders Company; 1991.

Hess TM. Adaptive aspects of social cognitive functioning in adulthood: age-related goal and knowledge influences. Social Cognition. 2006; 24:279–309.10.1521/soco.2006.24.3.279

Hess TM. Selective engagement of cognitive resources: Motivational influences on older adults' cognitive functioning. Perspectives on Psychological Science. in press.

Hess, TM.; Emery, L. Memory in context: The impact of age-related goals on performance. In: Naveh-Benjamin, M.; Ohta, N., editors. Perspectives on memory and aging. New York: Psychology Press; 2012. p. 183-214.

Hess TM, Emery L, Neupert SD. Longitudinal relationships between resources, motivation, and functioning. The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences. 2012; 67:299–308.10.1093/geronb/gbr100

Hess TM, Ennis GE. Age differences in the effort and cost associated with cognitive activity. The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences. 2012; 67:447–455.10.1093/geronb/gbr129

Hess TM, Germain CM, Swaim EL, Osowski NL. Aging and selective engagement: The moderating impact of motivation on older adults' resource utilization. The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences. 2009; 64B:447–456.10.1093/geronb/gbp020

Hess TM, Rosenberg DC, Waters SJ. Motivation and representational processes in adulthood: The effects of social accountability and information relevance. Psychology and Aging. 2001; 16:629–642.10.1037//0882-7974.16.4.629 [PubMed: 11766917]

Hogan MJ, James JE, McCabe TR, Kilmartin L, Howard S, Noone C. Cardiovascular reactivity of younger and older adults to positive-, negative-, and mixed-emotion cognitive challenge. Biological Psychology. 2012; 89:553–561.10.1016/j.biopsycho.2011.12.021 [PubMed: 22230758]

Jennings R, Brock K, Nebes R. Age and specific processing capacities: A cardiovascular analysis. Journal of Psychophysiology. 1990; 4:51–64. 1990-25051-001.

Jennings JR, Nebes R, Brock K. Memory retrieval in noise and psychophysiological response in the young and old. Psychophysiology. 1988; 25:633–644.10.1111/j.1469-8986.1988.tb01901.x [PubMed: 3241851]

Jennings JR, Nebes RD, Yovetich NA. Aging increases the energetic demands of episodic memory: a cardiovascular analysis. Journal of Experimental Psychology: General. 1990; 119:77–91.10.1037/0096-3445.119.1.77 [PubMed: 2141066]

Kim M, Beversdorf DQ, Heilman KM. Arousal response with aging: pupillographic study. Journal of International Neuropsychological Society. 2000; 6:348–50.10.1017/S135561770000309X

Kuchinsky SE, Ahlstrom JB, Vaden KI Jr, Cute SL, Humes LE, Dubno JR, Eckert MA. Pupil size varies with word listening and response selection difficulty in older adults with hearing loss. Psychophysiology. 2013; 50:23–34.10.1111/j.1469-8986.2012.01477.x [PubMed: 23157603]

Labouvie-Vief G. Cognition and equilibrium regulation in development and aging. Restorative Neurology and Neuroscience. 2009; 27:551–565.10.3233/RNN-2009-0512 [PubMed: 19847076]

Lakatta EG. Cardiovascular regulatory mechanisms in advanced age. Physiological Reviews. 1993; 73:413–467. [PubMed: 8475195]

Lerner JS, Tetlock PE. Accounting for the effects of accountability. Psychological Bulletin. 1999; 125:255–275. 1999-10106-00610.1037/0033-2909.125.2.255. [PubMed: 10087938]

McCabe DP, Roediger HL III, McDaniel MA, Balota DA, Hambrick DZ. The relationship between working memory capacity and executive functioning: evidence for a common executive attention construct. Neuropsychology. 2010; 24:222–243.10.1037/a0017619 [PubMed: 20230116]

McEvoy GM, Cascio WF. Cumulative evidence of the relationship between employee age and job performance. Journal of Applied Psychology. 1989; 74:11–17.10.1037/0021-9010.74.1.11

Murphy DR, Craik FIM, Li KZH, Schneider BA. Comparing the effects of aging and background noise on short-term memory performance. Psychology and Aging. 2000; 15:323–334.10.1037//0882-7974.15.2.323 [PubMed: 10879586]

Neupert SD, Soederberg LM, Lachman ME. Physiological reactivity to cognitive stressors: Variations by age and socioeconomic status. International Journal of Aging and Human Development. 2006; 62:221–235.10.2190/17DU-21AA-5HUK-7UFG [PubMed: 16625938]

Obrist, PA. Cardiovascular psychophysiology: A perspective. New York: Plenum; 1981.

Park, DC.; Payer, D. Working memory across the adult lifespan. In: Bialystok, E.; Craik, FIM., editors. Lifespan cognition: Mechanisms of change. New York: Oxford University Press; 2006. p. 128-142.

Park DC, Reuter-Lorenz P. The adaptative brain: aging and neurocognitive scaffolding. Annual Review of Psychology. 2009; 60:173–196.10.1146/annurev.psych.59.103006.093656

Peñáz, J. In: Albert, A.; Vogt, W.; Hellig, W., editors. Photoelectric measurement of blood pressure volume and flow in the finger; Digest of the 10th International Conference on Medical and Biological Engineering; Dresden, Germany: International Federation for Medical and Biological Engineering; 1973.

Piquado T, Isaacowitz D, Wingfield A. Pupillometry as a measure of cognitive effort in younger and older adults. Psychophysiology. 2010; 47(3):560–569. [PubMed: 20070575]

Piepoli M, Coats AJS, Adamopoulos S, Bernardi L, Feng YH, Conway J, Sleight P. Persistent peripheral vasodilation and sympathetic activity in hypotension after maximal exercise. Journal of Applied Physiology. 1993; 75(4):1807–1814. [PubMed: 8282635]

Pinto E. Blood pressure and ageing. Postgraduate Medical Journal. 2007; 83:109–114.10.1136/pgmj.2006.048371 [PubMed: 17308214]

Richter M. A closer look into the multi-layer structure of motivational intensity theory. Social and Personality Psychology Compass. 2013; 7(1):1–12.10.1111/spc3.12007

Richter M, Friedrich A, Gendolla GHE. Task difficulty effects on cardiac activity. Psychophysiology. 2008; 45:869–875.10.1111/j.1469-8986.2008.00688.x [PubMed: 18665860]

Rodeheffer RJ, Gerstenblith G, Becker LC, Fleg JL, Weisfeldt ML, Lakatta EG. Exercise cardiac output is maintained with advancing age in healthy human subjects: Cardiac dilatation and increased stroke volume compensate for diminished heart rate. Circulation. 1984; 69:203–213.10.1161/01.CIR.69.2.203 [PubMed: 6690093]

Salthouse TA. Resource-reduction interpretations of cognitive aging. Developmental Review. 1988; 8:238–272.

Salthouse TA. The processing-speed theory of adult age differences in cognition. Psychological Review. 1996; 103:403–428. 1996-01780-00110.1037//0033-295X.103.3.403. [PubMed: 8759042]

Salthouse TA. Consequences of age-related cognitive declines. Annual Review of Psychology. 2012; 63:201–226.10.1146/annurev-psych-120710-100328

Schapkin SA, Freude G, Gajewski PD, Wild-Wall N, Falkenstein M. Effects of working memory load on performance and cardiovascular activity in younger and older workers. International Journal of Behavioral Medicine. 2012; 19:359–371.10.1007/s12529-011-9181-6 [PubMed: 21786145]

Schmidt FL, Hunter JE. The validity and utility of selection methods in personnel psychology: Practical and theoretical implications of 85 years of research findings. Psychological Bulletin. 1998; 124:262–274.10.1037/0033-2909.124.2.262

Seeman TE, Robbins RJ. Aging and hypothalamic-pituitary-adrenal response to challenge in humans. Endocrinology Review. 1994; 15:233–260.

Smith BT, Hess TM. The impact of age and motivation on cognitive engagement. 2014 Manuscript in preparation.

Steptoe A, Kunz-Ebrecht SR, Wright C, Feldman PJ. Socioeconomic position and cardiovascular and neuroendocrine responses following cognitive challenge in old age. Biological Psychololgy. 2005; 6(9):149–166.10.1016/j.biopsycho.2004.07.008

Steptoe A, Moses J, Edwards S. Age-related differences in cardiovascular reactions to mental stress tests in women. Health Psychology. 1990; 9:18–34.10.1037/0278-6133.9.1.18 [PubMed: 2323326]

Taylor JA, Hand GA, Johnson DG, Seals DR. Sympathoadrenal-circulatory regulation during sustained isometric exercise in young and older men. American Journal of Physiology: Regulatory, Integrative, and Comparative Physiology. 1991; 261:R1061–R1069.

Tomporowski, PD. Cognitive energetics and aging. In: Spirduso, WW.; Poon, LW.; Chodzko-Zajko, W., editors. Exercise and its mediating effects on cognition. Champaign, IL, US: Human Kinetics; 2008. p. 85-109.

Tun PA, McCoy S, Wingfield A. Aging, hearing acuity, and the attentional costs of effortful listening. Psychology and Aging. 2009; 24:761–766.10.1037/a0014802 [PubMed: 19739934]

Uchino BN, Birmingham W, Berg CA. Are older adults less or more physiologically reactive? A meta-analysis of age-related differences in cardiovascular reactivity to laboratory tasks. Journal of Gerontology: Psychological Sciences. 2010; 65B:154–162.10.1093/geronb/gbp127

Uchino BN, Uno D, Holt-Lunsted J, Flinders JB. Age-related differences in cardiovascular reactivity during acute psychological stress in men and women. The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences. 1999; 54B:P339–P346. 1999-15844-001.

Van Gerven PWM, Paas F, Van Merriënboer JJG, Schmidt HG. Memory load and the cognitive pupillary response in aging. Psychophysiology. 2004; 41:167–174. [PubMed: 15032982]

Verhaeghen P, Steitz DW, Sliwinski MJ, Cerella J. Aging and dual-task performance: A meta-analysis. Psychology and Aging. 2003; 18:443–460. [PubMed: 14518807]

Vick, RL. Contemporary medical physiology. Menlo Park, CA: Addison-Wesley Publishing Co; 1984.

Westbrook A, Kester D, Braver TS. What is the subjective cost of cognitive effort? Load, trait, and aging effects revealed by economic preference. PLoS ONE. 2013; 8:e68210.10.1371/journal.pone.0068210 [PubMed: 23894295]

Wright, RA. Brehm's theory of motivation as a model of effort and cardiovascular response. In: Gollwitzer, PM.; Bargh, JA., editors. The psychology of action: Linking cognition and motivation to behavior. New York: Guilford; 1996. p. 424-453.

Wright RA, Dill JD. Blood pressure responses and incentive appraisals as a function of perceived ability and objective task demand. Psychophysiology. 1993; 30:152–160.10.1111/j.1469-8986.1993.tb01728.x [PubMed: 8434078]

Wright RA, Dill JC, Geen RG, Anderson CA. Social evaluation influence on cardiovascular response to a fixed behavioral challenge: Effects across a range of difficulty levels. Annals of Behavioral Medicine. 1998; 20:277–285.10.1007/BF02886377 [PubMed: 10234421]

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Wright RA, Junious TR, Neal C, Avello A, Graham C, Herrmann L, Walton N. Mental fatigue influence on effort-related cardiovascular response: Difficulty effects and extension across cognitive performance domains. Motivation and Emotion. 2007; 31:219–231.10.1007/s11031-007-9066-9

Wright, RA.; Kirby, LD. Effort determination of cardiovascular response: An integrative analysis with applications in social psychology. In: Zanna, MP., editor. Advances in experimental social psychology. Vol. 33. New York: Academic Press; 2001. p. 255-307.

Wright RA, Martin RE, Bland JL. Energy resource depletion, task difficulty, and cardiovascular response to a mental arithmetic challenge. Psychophysiology. 2003; 40:98–105.10.1111/1469-8986.00010 [PubMed: 12751807]