Interactions between Threat and Executive Control in a Virtual Reality Stroop Task

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Abstract—Understanding the ways in which persons rapidly transfer attention between tasks while still retaining ability to perform these tasks is an important area of study. Everyday activities commonly come in the form of emotional distractors. A recently developed Virtual Reality Stroop Task (VRST) allows for assessing neurocognitive and psychophysiological responding while traveling through simulated safe and ambush desert environments as Stroop stimuli appear on the windshield. We evaluated differences in psychophysiological response patterns associated with completion of an affective task alone versus completion of an affective task that also included a Stroop task. The VRST elicited increased heart rate, respiration rate, skin conductance level, and number of spontaneous fluctuations in electrodermal activity. Increased cognitive workload was found to be associated with the more cognitively challenging Stroop conditions which led to an increase in response level. This expands on previous findings and indicates that allocating attention away from the environment and toward Stroop stimuli likely requires greater inhibitory control. This is corroborated by behavioral findings from previous investigations with the VRST. The VRST revealed that the increased difficulty found in tasks like the Stroop interference task directly evoke autonomic changes in psychophysiological arousal beyond the threatening stimuli themselves.

Index Terms—Affective computing, Psychology, Arousal Classification, Affect Recognition, Virtual Reality, Stroop Task.

1 INTRODUCTION

Activities of daily living such as navigating and talking require the use of executive functions to simultaneously attend to several tasks and inhibit prepotent responses to various stimuli. Executive functions draw upon supervisory attentional networks that include: selective attention, inhibitory control, planning, problem solving, and some aspects of short-term memory [1]. Understanding the ways in which persons divide attention among several tasks, or rapidly transfer attention between tasks, while still retaining ability to perform these tasks is an important area of study. One of the most widely used tasks for cognitive evaluation of the executive aspects of attention control is the Stroop [2] task, in which the participant is instructed to indicate the color font (e.g., red) in which a word is displayed while ignoring the semantic content of the word (e.g., blue; see [3]). When the “font color” is incongruent with the “semantic word” conflict (cognitive control demand) is induced between task-relevant stimuli (font color) and distracting stimuli (the semantic content). Studies assessing cognitive control have yielded a description of an underlying neural network for conflict detection and resolution [4], [5].

In addition to cognitive conflict, everyday activities commonly come in the form of emotional distracters [6]. Affective responses to emotional distractors may be understood as multimodal events in response to a stimulus that has particular significance for the participant, often signifying a potential threat or reward. Affective stimuli are particularly potent distracters that can reallocate processing resources and impact attentional performance [7], [8]. Enhanced understanding of the effect of threatening stimuli upon executive functions also has important implications for affective disorders that are characterized by increased susceptibility to affective distraction [9]. As one precondition for a specific affective experience, emotion may include automatic and controlled recognition and evaluation of a stimulus [10]. In addition to the appraisal of a stimulus, affective reactions are characterized by psychophysiological changes (e.g., alterations in skin conductance and heart rate; as well as behavioral approach or avoidance) and involve a number of subcomponents occurring in frontal subcortical circuits [11], [12], [13].

According to models of neurovisceral integration, autonomic, attentional, and affective systems are simultaneously engaged in the support of self-regulation [14], [15], [16]. Working from a neurovisceral integration model, Capuana et al [17] examined whether increase in difficulty of an executive control task would increase the need for cardiac autonomic regulation in maintaining effective cognitive control. Results indicate that pre-task respiratory sinus arrhythmia predicted accuracy best on a Stroop task when errors resulted in financial loss. Greater respiratory sinus arrhythmia has also been found when participants have had to execute correct responses more quickly in the context of an emotional Stroop task [18]. Several studies using the classical Stroop paradigm have found performance-related reductions in heart rate and respiratory sinus arrhythmia [19], [20], [21], [22]. Another psychophysiological metric that has been found to increase as workload increases is skin conductance. During the Stroop task, incongruent stimuli, associated with a higher degree of task difficulty than congruent stimuli, has been found to elicit larger skin conductance responses [23]. Increased task difficulty using an n-back task
also results in increased skin conductance levels [24]. Additionally, numerous studies using various cognitive tasks have evidenced increased heart rate associated with increased cognitive workload [24], [25], [26], [27]. An increase in respiratory rate has been consistently associated with increased cognitive demand [24], [28], [29].

A recently developed virtual reality-based Stroop task allows for assessing neurocognitive and psychophysiological responding while riding in a virtual High-Mobility Multi-purpose Wheeled Vehicle (HMMWV) through safe and threatening zones of a desert environment as Stroop stimuli appear on the windshield. The Virtual Reality Stroop Task (VRST) has been validated as a measure of supervisory attentional processing and was designed to emulate aspects of the classic Stroop and emotional Stroop tasks [30]. When compared to paper-and-pencil, as well as computer-automated versions of the Stroop, the VRST appears to have enhanced capacity for providing an indication of a participant’s reaction time and ability to inhibit a prepotent response while immersed in a military relevant simulation [31], [32] that assesses arousal in safe and ambush zones [33], [34]. However, whether the delayed reaction times and arousal levels exhibited by the individuals arise from the challenge of the task, the stimulation of the environment, or an interaction of both is unclear. The VRST requires the individual to attend away from a threatening stimulus and towards the task-relevant stimulus in order to provide the correct response. The goal of the current study was to build upon prior work with the VRST and investigate psychophysiological responses of persons at various levels of threat and attention allocation. To do so, we examined psychophysiological responses to task-irrelevant threatening stimuli during two counterbalanced conditions: 1) Affective Condition, in which the participant rides through a virtual Iraqi environment with varying levels of threat; and 2) Cognitive Control x Affective Condition, in which the participant rides through the same environment (high and low threat zones) while completing a Stroop task.

2 METHODS
2.1 Hypotheses
This study was designed to compare the psychophysiological responses elicited by both the Affective Condition and the Cognitive Control x Affective Condition. Hence, psychophysiological measures were used to assess responses to varying levels of threat experienced by the participant, and how those responses were affected by the addition of the Stroop task. We hypothesized the following:

1) The addition of the Stroop task to the virtual environment would elicit increased psychophysiological activation, such as increased heart rate, respiration rate, skin conductance level (SCL), and number of spontaneous fluctuations (SFs) in electrodermal activity.

2) Increased cognitive workload associated with the more cognitively challenging Stroop conditions would lead to an increase in response level.

3) Increased threat was also expected to lead to increased psychophysiological responding.

Cognitive control has been found to be impacted by influences from increased arousal level [14], [35]. Given our interest in the combined effects of the cognitive-control task and threat it was also hypothesized that:

4) There would be an interaction between threat intensity and whether the participant was in the Affective Condition or Cognitive Control x Affective Condition, such that greater differences between responses during high and low threat would be evident during the Cognitive Control x Affective Condition. The Cognitive Control x Affective Condition would accentuate response differences between high and low threat regions of the VE.

5) There would be an interaction between the Affective Condition and Cognitive Control x Affective Condition and the cognitive task difficulty in the Cognitive Control x Affective Condition. Given that participants were required to decouple attention and threat appraisal in order to provide a goal-directed behavior, it was hypothesized that there would be a greater difference in psychophysiological response to Stroop difficulty levels during the Cognitive Control x Affective Condition.

2.2 Participants
The University’s Institutional Review Board approved the study. A total of 50 college-aged subjects participated in the study. The age range of participants was 18 to 28 years of age (Age: $M=19.71$; $SD=2.82$). Participants were 75 percent female. The education range of participants was 12 to 15 years (Education: $M=13.6$; $SD=1.07$). No significant differences were found for age, gender, or education. After informed consent was obtained, basic demographic information was recorded. Participants were also given a medical health history form to assess the presence of any mental or physical disorders that may have hindered their performance; however none of the participants were excluded from analyses for responses given on this form.

2.3 Design and Measures
The current study employed a within-subjects design, which included two counterbalanced and separate experimental task sessions taking place in the same virtual environment. One experimental run included an Affective Condition, in which participants rode along a desert road in the virtual Iraqi environment. In the other experimental run, Cognitive Control x Affective Condition, participants were exposed to the same environmental stimuli as were present in the Affective Condition, however during the Cognitive Control x Affective Condition, Stroop stimuli were presented. The Affective Condition was employed specifically to allow for the examination of the differences in psychophysiological response patterns between exposure to a threatening environment without (Affective Condition) and with (Cognitive Control x Affective Condition)
the inclusion of a challenging cognitive control task (e.g., Stroop). The order of the task sessions was counterbalanced across participants.

2.3.1 Affective Condition. During the Affective Condition, participants were asked to ride in a virtual HMMWV that included safe and dangerous regions. Psychophysiological responses were recorded throughout the participants’ period of immersion within the virtual environment. Electrocardiographic activity (ECG), electrodermal activity (EDA), and respiration were the psychophysiological measures recorded as participants rode in the simulated HMMWV through alternating safe and ambush zones. Amongst safe zones, little activity in the VE was presented aside from landscapes and scenery associated with a desert road. During the ambush zones, gunfire, explosions, and shouting amongst other stressors were presented throughout the simulation. The participants experienced four safe and ambush zones designed to manipulate levels of arousal. The order of threat level presentation was counterbalanced across participants, such that half of the participants experienced ambush zones first, while the other half were first exposed to safe zones.

2.3.2 Cognitive Control \times Affective Condition. In a separate experimental session, the VRST was utilized to create a Cognitive Control \times Affective Condition of riding in the HMMWV through the simulated desert environment and completing the VRST. The VRST involves the participant being immersed in the HMMWV as Stroop stimuli appear on the windshield. Single-item presentations of Stroop stimuli are used in the VRST and the test requires an individual to press one of three computer keys to identify each of three colors (i.e., red, green, or blue). The VRST adds a simulation environment with military relevant stimuli in safe and ambush settings.

During the Cognitive Control \times Affective Condition, the VRST was completed during exposure to the same safe and ambush zones found in the Affective Condition. The presentation of the Stroop stimuli consisted of four modes: 1) word-reading, 2) color-naming, 3) simple interference (stimuli presented in the middle of windshield), and 4) complex interference (stimuli presented in variable locations on windshield). Each Stroop mode was experienced once in an ambush zone and once in a safe zone. The presentation speed of individual stimuli was user-defined, meaning that the subsequent stimulus did not appear until the appropriate key was pressed in response to the stimulus currently being viewed.

2.4 Apparatus

The apparatus used for the virtual HMMWV included a Pentium 4 desktop computer with a 3 GHz Processor; 6 GB of RAM; and an nVidia GeForce 6800. An eMagin Z800 head-mounted display (HMD) with an InterSense Intersense aCube 2+ attached for tracking was used to present the virtual environment to the participant. To increase the potential for sensory immersion, each participant’s chair was seated on a three-foot square tactile transducer platform with six Aura bass shaker speakers (AST-2B-04, 4Ω 50W Bass Shaker). The tactile transducer was powered by a Sherwood RX-4105 amplifier with 100 Watts per Channel x 2 in Stereo Mode.

Animation software was utilized for development of the virtual Iraqi/Afghani and HMMWV VRST environment. The environments were rendered in real time using a graphics engine with a fully customizable rendering pipeline, including vertex and pixel shaders, shadows, bump maps, and screenspace geometric primitives. A MATLAB scoring program and human-computer interface were employed for data acquisition, to guide stimulus presentation, and for psychophysiological monitoring. The scoring program and interface also allowed for key events in the environment to be logged and time stamped with millisecond temporal accuracy.

Feature extraction and optimal response classification for VRST and psychophysiological responses were examined using a MATLAB scoring program designed specifically for studies using the VRST. This allowed for assessment of performance validity (suboptimal effort) and screening for outliers to establish data integrity: 1) identification of outliers as observations exceeding three standard deviations from the median reaction time; 2) exclusion of observations that are in both the top one percent in speed and simultaneously in the bottom one percent of accuracy; and 3) filtering and pattern recognition assessment for establishing feature sets using support vector machine classifiers.

2.5 Dependent Variables

All psychophysiological response measures were recorded simultaneously throughout the experiment at a sampling rate of 1000 Hz using a Biopac MP150 system. The MATLAB scoring program and interface were utilized for logging all raw psychophysiological data and also allowed for key events in the environment to be logged and time stamped with millisecond temporal accuracy. The psychophysiological variables utilized were:

1. The mean interbeat interval (IBI) from the ECG recordings.
2. The mean interbreath interval (IBRI) from the respiration recordings.
3. The mean SCL.
4. The number of spontaneous fluctuations (SFs) in electrodermal activity.

2.5.1 Electrocardiographic Activity. ECG activity was recorded using a Lead 1 electrode placement. Electrode sites were cleaned with alcohol prep pads in order to improve contact. IBIs were scored as the time difference between successive R waves in the ECG signal. IBIs were used as the dependent variable analyzed instead of heart rate because of a lowered susceptibility to artifact due to differences in baseline values. R-wave peak detection was conducted with use of an in-house designed MATLAB data scoring program, and each peak was checked manually for detection accuracy.

2.5.2 Respiration. A transducer belt was placed around each participant’s chest to measure rate of respiration. A band pass filter between 0.05 Hz and 1 Hz was applied to the signal. Similar to the calculation of IBIs, IBRIs were cal-
culated as the time difference between consecutive positively deflecting peaks in the signal, which are indicative of inhalation peaks. All peaks were initially located with the MATLAB scoring program and were checked for accuracy manually.

2.5.3 Electrodermal Activity. EDA was recorded with use of two sensors attached to the volar surface of the distal phalanges of the index and middle fingers of the non-dominant hand to measure skin conductance responses. Mean skin conductance levels (SCLs) were calculated for each zone, as were the number of SFs, which were quantified as an increase in the signal of more than 0.02 μS with a rise-time of 1 to 3 seconds to peak following response onset.

2.6 Analytic Strategy

An initial set of analyses were employed to examine differences in response to completing both the Affective Condition and the Cognitive Control x Affective Condition, as well as differences between safe and ambush zones as well as high and low cognitive workload related to the VRST. A 2 (task level) by 2 (threat level) by 2 (congruency) repeated measures ANOVA was applied to each dependent psychophysiological variable. The “task level” variable refers to whether the participant was experiencing the Affective Condition or the Cognitive Control x Affective Condition. “Threat level” is in reference to the high and low threat zones, and the “congruency” variable relates to the cognitive workload level associated with the Stroop stimuli in the Cognitive Control x Affective Condition. The color-naming and word-reading conditions were combined to create the “congruent” condition, whereas the simple and complex interference conditions were combined to form the “incongruent” condition. The incongruent condition is associated with greater cognitive workload than the congruent condition [30]. Though the Affective Condition did not include Stroop stimuli, the same zones that included congruent or incongruent stimuli in the Cognitive Control x Affective Condition were compared to the zones that matched the order of congruency presentation in the Affective Condition.

A second set of analyses were designed to examine interactions between task level, threat level, and congruency while taking behavioral VRST performance into account. Each dependent psychophysiological measure was weighted by the individual participant’s performance during the Cognitive Control x Affective Condition. Psychophysiological response means were multiplied by the percentage of correct responses given for that subject in each of the 8 zones in order to calculate the weighted variables. Following the weighting of the psychophysiological responses gleaned during the Cognitive Control x Affective Condition, the same 2 (task level) by 2 (threat level) by 2 (congruency) repeated measures ANOVA was again used for each of the four distinct psychophysiological response measures.

A sequentially rejective test procedure based on a modified Bonferroni inequality was used on significant results to prevent inflation of Type I error rates [37]. Additionally, a Greenhouse–Geisser correction was used for all reported main effects and interactions with greater than one degree of freedom.

3 Results

3.1 Affective Condition, however during the Cognitive Control x Affective Condition

A main effect of task level was revealed with the ANOVA involving data that was not weighted for performance for each of the dependent variables. The Cognitive Control x Affective Condition resulted in shorter IBIs (i.e., increased heart rate), $F(1, 49) = 4.25, p < 0.05$, as well as shorter IBIs (i.e., increased rate of respiration), $F(1, 49) = 35.21, p < 0.001$. The Cognitive Control x Affective Condition was also associated with an increase in SCL, $F(1, 49) = 19.94, p < 0.001$, and a greater number of SFs, $F(1, 49) = 36.13, p < 0.001$.

3.2 Safe vs. Ambush (high threat) Zones

A significant threat level main effect was apparent for each of the dependent variables such that increased responding was associated with exposure to the high threat zones. The high threat zones resulted in shorter IBIs, $F(1, 49) = 9.04, p < 0.01$, and IBIs, $F(1, 49) = 29.84, p < 0.001$. High threat zones also elicited increased SCLs, $F(1, 49) = 21.20, p < 0.001$, and a greater number of SFs, $F(1, 49) = 14.08, p < 0.001$.

3.3 Congruent vs. Incongruent

The more difficult incongruent stimuli led to significantly shorter IBIs, $F(1, 49) = 18.00, p < 0.001$. Though not significant, a trend toward increased respiration rate leading to shorter IBIs was also present, $F(1, 49) = 3.82, p = 0.05$. Electrodermal activity revealed unexpected results such that lower SCLs, $F(1, 49) = 17.24, p < 0.001$, and fewer SFs, $F(1, 49) = 6.25, p < 0.05$, were associated with the more difficult incongruent task conditions.

3.4 Task Level by Threat Level Interaction

Utilizing the ANOVAs that included performance weighting, a significant interaction between task level and threat level was uncovered in regards to IBI responses, such that there was a greater difference between safe and ambush (high threat) zones during the Cognitive Control x Affective Condition, $F(1, 49) = 10.28, p < 0.01$. Paired samples t-tests revealed that while differences between safe and ambush (high threat) zones in the Cognitive Control x Affective Condition were significant, $t(49) = 4.33, p < 0.01$, this was not the case during the Affective Condition (Fig. 1).

3.5 Task Level by Congruency Interaction

As hypothesized, a significant difference in responding between congruent and incongruent zones was elicited by the Cognitive Control x Affective Condition regarding IBIs, $t(49) = 4.89, p < 0.001$, but not during the Affective Condition, leading to a significant interaction between task level and congruency, $F(1, 49) = 56.62, p < 0.001$ (Fig. 2). The same interaction was revealed in regards to IBIs, $F(1, 49) = 4.44, p < 0.05$. A greater difference in IBIs in relation to congruency was demonstrated during the Cognitive Control x Affective Condition $t(49) = 4.73, p < 0.001$, such
that shorter IBrIs were exhibited during the more difficult incongruent condition. IBrI differences between congruent and incongruent conditions during the Affective Condition were not significant. Also hypothesized, the electrodermal responses were lower in the more difficult incongruent conditions and this effect was accentuated during the Cognitive Control x Affective Condition. The interaction was significant and followed the same pattern for both SCLs, $F(1, 49) = 6.77, p < 0.05$, and SFs, $F(1, 49) = 6.79, p < 0.05$.

4 DISCUSSION

4.1 Psychological response patterns associated with Affective vs. Cognitive Control x Affective Conditions

For our primary analysis in this study we sought to evaluate differences in psychophysiological response patterns associated with completion of an Affective task versus completion of a Cognitive Control x Affective Condition. As expected, the Cognitive Control x Affective Condition elicited increased psychophysiological activation, such as increased heart rate, respiration rate, skin conductance level (SCL), and number of spontaneous fluctuations (SFs) in electrodermal activity. Increased cognitive workload was found to be associated with the more cognitively challenging Stroop conditions which led to an increase in response level. This expands on previous findings and indicates that the “Cognitive Control x Affective Condition” of having to allocate attention away from the environment and toward the Stroop stimuli likely requires greater inhibitory control. Indeed, this is corroborated by behavioral findings from previous investigations with the VRST [30].

4.1.1 Skin conductance will generally increase as workload increases. Incongruent stimuli during the Stroop task were associated with a higher degree of task difficulty than congruent stimuli and elicited larger skin conductance responses [23]. Additionally, participants in the Stroop task evidenced larger SCRs when responding to a stimulus incorrectly, and longer response times were associated with larger SCRs as well. These findings, along with our results, support the notion that EDA provides a measure of overall activation—more difficult tasks created a greater cognitive workload and resulted in increases in the SCR. Further support for our findings can be found in a study that found increased task difficulty using an n-back task resulted in increased skin conductance levels [24]. Collaborating evidence can also be found in a study that examined the time interval between SFs (similar to counting the number of SFs within a condition) as its measure of workload assessment as participants rode in a car and performed cognitive tasks [38]. SF rate increased significantly when participants performed cognitive tasks while driving compared to baseline and compared to driving with no additional cognitive task. These findings suggest that SFs might be a useful measure of workload in assessment for simulation technologies.

4.1.2 Heart Rate generally increases with cognitive workload. Support for our findings related to HR and the Stroop was found in Fournier et al’s [39] study, in which HR increased significantly as participants were subjected to more challenging multi-task conditions compared to single-task conditions, and that HRV was reduced in the more difficult multi-task conditions, which is corroborated by numerous studies examining HRV and workload (see [40] for review). Mental arithmetic also produces increases in HR as task difficulty increases [27]. Verwey and Veltman [38] subjected participants to cognitive tasks while driving in comparison to a control task in which no additional cognitive task was performed while driving. Participants evidenced decreased IBIs (which translates to an increase in HR) and reduced HRV when performing the cognitive tasks.
4.1.3 Association between respiratory rate and cognitive workload. Our findings of an increase in respiratory rate with increased cognitive demand are supported by a number of studies [24], [28], [29]. Backs & Selijos [28] found that rates of respiration increased as task difficulty increased in a working memory task. During an air traffic control simulation with three levels of task difficulty, air traffic controllers exhibited increased rates of respiration as task difficulty increased [29]. Respiration increases when participants perform a difficult multi-task condition when compared to a single-task condition [39]. Brookings et al. [29] reported increased respiration rates with increased levels of difficulty in an air traffic control simulation. In accordance with these findings, Veltman & Gaillard [40] found that pilots in a flight simulator who were asked to fly through varying flight conditions (e.g. tunnel and pursuit conditions) and perform cognitive tasks of varying difficulty exhibited increased respiration rates with increased task difficulty.

In a study involving a driving simulation which included both low and high levels of secondary cognitive task conditions, respiration rate was a sensitive measure of workload intensity [24]. During the low level task difficulty, respiration rate did not increase above baseline driving conditions, and performance on this task was nearly perfect across participants ($n = 121$). However, during the high difficulty task condition, respiration rate increased and driving performance waned. These findings demonstrate the effectiveness of respiration rate as a means of monitoring workload, and provide support for the incorporation of respiration rate as an indicator of overload in future adaptive automation research design.

4.2 Secondary Analysis: affective processing in Safe vs. Ambush (high threat) Zones

A secondary goal of this study was to investigate the utility of our environment to offer varying levels of stimulus threat to impact the participant’s experience of the VE. Our analysis revealed that increased threat led to increased psychophysiological responding.

4.2.1 Skin conductance responses were impacted by fear inducing or stressful stimuli. Of particular interest in the current study is the way skin conductance responses are affected by fear inducing or stressful stimuli. Öhman & Soares [44] found that subjects high in fear for a certain biologically prepared stimulus (i.e. pictures of snakes or spiders) will exhibit potentiated electrodermal responses when presented with pictures of their specifically feared stimulus. Likewise, Globisch et al. [43] found that fearful subjects showed increased skin conductance responses to feared stimuli relative to neutral and positive stimuli. These findings indicate that greater levels of fear responding (e.g., to the high threat zones) result in greater skin conductance response potentiation and increased skin conductance levels.

4.2.2 Heart rate and defensive responding during highly...
arousing and fearful situations. Our findings comport well with findings that heart rate responding during highly arousing and fearful situations is generally associated with defensive responding, which results in increased heart rate, as opposed to orienting responses which reduce heart rate [44], [45]. Van Oyen, Witvliet, and Vrana [46] found the greatest increase in heart rate acceleration when startling probes were presented during a high arousal mental imagery task compared to low arousal imagery. Fearful subjects exposed to prolonged fear inducing situations have also been evidenced to maintain a sustained heightened heart rate compared to controls during the exposure period [47]. In general, increased arousal caused by fearful situations tends to result in heart rate increases.

Tonic HR measures are also affected by threatening stimuli as fearful participants exposed to prolonged fear inducing situations have shown a tendency to maintain a sustained heightened HR compared to control participants during the same exposure period [47]. Thus, cardiovascular responding can be an informative measure when differentiating between the effectiveness of fear elicitation of different stimulus presentation modalities.

4.2.3 Increased respiration in response to heightened levels of arousal associated with threat. Our findings are supported by the literature, in that respiration rate has consistently been shown to increase in response to heightened levels of arousal associated with fear [48]. Etzel et al. [49] found that music clips that subjects rated as “fearful” led to significantly increased rates of respiration compared “sad” music clips. Likewise, responses to fear inducing film clips have been demonstrated to significantly increase respiration rates compared to sad and neutral film clips [50]. Mental imagery of fearful events has also been shown to increase rates of respiration [51]. Fenz and Jones [52] assessed respiration rates of novice and experienced skydivers, and found that novice skydivers evidenced steadily increasing rates of respiration leading up to the jump, while experienced jumpers exhibited an initial increase in the early jump sequence, but gradually slowed as the moment of the jump approached. Pleasant relaxation, on the other hand, tends to lead to decreases in respiration rates. Nakamura [53] found that decreased respiration rates were associated with listening to music when ratings of calmness were high, however music that was rated cheerful or powerful caused respiration rate increases. This suggests that respiration rates are a better index of arousal than valence. Calm relaxation relates to decreases in respiration rate, while excitement and arousal, whether positive or negative, results in increased rates of respiration.

4.3 Task Level by Threat Level Interaction

Hypotheses 4 and 5 suggested there would be an interaction between threat intensity and whether the participant was completing the Affective Condition or Cognitive Control x Affective Condition, such that greater differences between responses during safe and ambush (high threat) would be evident during the Cognitive Control x Affective Condition. Studies have found that “ventral affective” processing is favored over “dorsal executive” processing in the presence of threatening stimuli [54]. When moving from threat-neutral to negatively valenced distracters in an executive function task, the “ventral affective” brain areas show increased activation; and greater deactivation is found in more “dorsal executive” brain areas [8], [55], [56], [57], [58].

Findings from our study reveal a significant interaction between task level and threat level for IBI responses, but not for other psychophysiological metrics. While differences between safe and ambush zones in the Cognitive Control x Affective Condition were significant this was not the case during the Affective Condition. The lack of significant interaction between threat intensity and complexity (Affective Condition versus Cognitive Control x Affective Condition) for psychophysiological metrics other than IBIs may reflect the fact that while heart rate is influenced primarily by a behavioral “activation” system involved in responding during appetitive reward-seeking and during active avoidance, electrodermal activation is influenced primarily by a behavioral “inhibition” system involved in responding to passive avoidance or to frustrating nonreward [59], [60].

Acute mild psychological stress impairs “dorsal executive” function [61], [62], [63], [64], [65], [66], and heightens the sensitivity of the “ventral affective” system towards threatening stimuli [67]. Given that a significant interaction between task level and threat level was only uncovered for IBI responses, it may be that participants experienced the task by threat condition through “activation” (heart rate) instead of “inhibition” (skin conductance). Hence, as a possible post-hoc account, it might be assumed that heart rate and SCL reflect different sub-processes, which were differently influenced by the experimental manipulation. Further, while skin conductance responses to threatening stimuli are unidirectional, heart rate responses to threatening stimuli initially decelerate after stimulus onset (e.g., orienting response), then accelerate and later decelerate again [44], [68]. While electrodermal activity offers trial-by-trial visibility and utility as a general arousal/attention indicator, heart rate may better reflect the interaction due to its potential differentiation of psychological and physiological states.

4.4 Task Level by Congruency Interaction

It was hypothesized that there would be a greater difference in psychophysiological response to Stroop difficulty levels during the Cognitive Control x Affective Condition. As expected, a significant difference in responding between congruent and incongruent zones was elicited by the Cognitive Control x Affective Condition regarding HR, but not during the Affective Condition, leading to a significant interaction between task level and congruency. The same interaction was revealed in regards to respiration rate. A greater difference in respiration rate in relation to congruency was demonstrated during the Cognitive Control x Affective Condition, such that increased rates were exhibited during the more difficult incongruent condition. Respiration rate differences between congruent and incongruent conditions during the Affective Condition were not significant. These results may indicate that the cognitive effort required to carry out both allocation of attention
away from task-irrelevant distractors (the environment) toward task-relevant stimuli (Stroop stimuli) and resolution of the color/word conflict presented in the Stroop stimuli may increase in an additive fashion. Also hypothesized, the electrodermal responses were lower in the more difficult incongruent conditions and this effect was accentuated during the Cognitive Control x Affective Condition. The interaction was significant and followed the same pattern for both SCLs and SFs.

The “dorsal executive” system has been found to activate to increased SCR during inhibition tasks that require deliberately stopping a prepared motor response, suggesting that it mediates changes in arousal following exposure to external stimuli [69]. A relationship between dorsal executive activity and autonomic bodily responses has been found for heart rate in reaction time [70], skin conductance [71], [72], and blood pressure [73]. Further evidence in support of our findings can be found in Critchley et al’s [74] quantification of changes in arousal from changes in pupil size and found that dorsal anterior cingulate activity reflected both performance error and pupillary responses in a Stroop task.

Taken together these results indicate that the VRST may be able to recruit both dorsal and ventral processes in the Cognitive Control x Affective Condition. That is to say, individuals in this condition must not only monitor conflict within the Stroop task (color/word), but must also monitor and actively release their attention from the emotional distractor ventral “affective” pathway. Evidence from this investigation lends credence to one prevailing hypothesis about cognitive control in tasks eliciting an emotional response. Specifically, those tasks requiring disengagement from an emotional distractor recruit dorsal anterior regions during negative valence evaluation as well as ventral “affective” regions during inhibition and regulation. Thus, negative valence stimuli recruit both dorsal and ventral processes [75]. Unlike tradition emotion-evoking Stroop tasks, the VRST employs both an emotional distractor and a separate but co-occurring conflict resolution task.

Because of this Cognitive Control x Affective approach, we were able to examine the impact of both task-irrelevant emotional distraction, task-relevant conflict resolution, and the interaction of the two co-occurring processes. The psychophysiological data presented here offer one way by which we may disentangle the differential processes of conflict due to emotional distraction, and conflict due to task difficulty. Increased skin conductance was observed in response to the emotion-only Affective Condition, yet was attenuated during the threat x Stroop (interference) Cognitive Control x Affective Condition. Heart rate and respiratory responsiveness, on the other hand, were increase in both the Affective Condition and the Cognitive Control x Affective Condition. Thus the increase in cognitive workload induced by the Cognitive Control x Affective Condition differentially impacted disparate autonomic processes.

5 STRENGTHS, LIMITATIONS, AND FUTURE

DIRECTIONS

To our knowledge, this is the first study to examine neurocognitive and affective responses to a virtual reality-based Stroop platform. The current investigation benefited from a number of methodological strengths. We measured both psychophysiological and performance metrics, both necessary for a more complete understanding of cognitive control and emotion.

Nonetheless, a number of limitations of the current project should be considered. A direct comparison of the psychophysiological results while immersed in a VRST and neuroimaging has not been made. It would be interesting for future studies to incorporate the VRST into a neuroimaging protocol to directly compare autonomic results from psychophysiological metrics to specific brain regions gleaned from refined neuroimaging studies.

In addition, an increased understanding of the effects of an immersive virtual environment would further validate the use of the VRST. While it is promising to know that psychophysiological metrics can be effective in emotion elicitation, it would be of interest to know whether emotional responses are further elucidated when viewed via neuroimaging. Virtual environments can be rendered in a three-dimensional landscape. Greater levels of interactivity afforded by a virtual environment add to an increased feeling of presence or “being there” [76] and lead to more pronounced physiological responses to virtual stimuli [77], [78], [79]. Neuroimaging studies would be the next logical step for elucidating the neurocognitive and affective properties of the VRST.

6 CONCLUSION

One of the main goals of this experiment was to examine differences in psychophysiological response patterns associated with completion of an Affective Condition of a Cognitive Control x Affective Condition. Supporting previous studies, the virtual reality environment Stroop platform was able to show that the increased difficulty found in tasks like the Stroop interference task directly evoke autonomic changes in psychophysiological arousal. We also showed that the Cognitive Control x Affective Condition tasks could elicit increased psychophysiological activation. Increased cognitive workload was found to be associated with Stroop conditions. Increased threat was shown to lead to increased psychophysiological responding and supervisory attentional processing was impacted by arousal level. Whilst the executive control network is frequently coactivated with emotion networks in tasks of attention, working memory, and response selection, we found potential evidence for salience activation in response to threats. Given our interest in the combined effects of the “executive control network” and the “salience network” we explored the interaction between threat intensity and task complexity. We found that greater differences between responses during high and low threat...
are evident during the Cognitive Control x Affective Condition.

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REFERENCES


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