The Autonomic Correlates of Listening Effort.

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Thesis Abstract

For those with hearing impairment, listening in daily life communication requires significant mental effort, even when using a hearing aid. This increased daily effort causes fatigue and reduced well-being. In recent years, researchers have utilised physiological measures to quantify listening effort; however, the chosen methods are seldom driven by psychophysiological theories. Despite a considerable number of empirical articles, the evidence in support of the physiological quantification of listening effort is inconclusive.

The experiments within this thesis were driven by empirical evidence on autonomic nervous system activity and motivational intensity theory (Brehm, 1989; Wright, 1996), to provide a systematic, inclusive and theory-driven examination of the physiological correlates of listening effort. It was hypothesised that, to avoid wasting essential resources, (listening) effort occurs as a function of (listening) demand while success is possible, and the required effort is justified. Listening effort was quantified as myocardial reactivity driven by parasympathetic nervous system withdrawal and sympathetic nervous system activation.

Utilising a systematic and theory-driven approach, three phases of experiments tested the multi-layer predictions of motivational intensity theory in relation to effortful listening. The first phase provided empirical evidence for the impact of listening demand on listening effort-driven myocardial sympathetic activation (quantified as pre-ejection period), only while successful speech comprehension was possible. Subjective effort increased alongside myocardial sympathetic activity but was not limited by the possibility of success. The second phase provided the first evidence for the impact of reward (the importance of success) on listening effort-driven myocardial sympathetic activation (pre-ejection period) in listening tasks with an unclear performance standard. Subjective effort increased, alongside myocardial

sympathetic activity, as a function of reward for successful comprehension. The final phase, grounded in the results from phase one and two, provided evidence of a trend for cardiovascular reactivity that partially supported the final hypothesis that an interaction effect between listening demand and reward should affect listening effort. However, the final experiment failed to provide evidence for specific cardiovascular reactivity caused by listening effort-related myocardial sympathetic activation as a function of the listening demand- reward interaction.

Overall, this thesis provided evidence for the hypothesis that, listening effort driven by myocardial sympathetic activation occurs as a function of listening demand while task success is both possible and the required effort is justified by the importance of successful comprehension. No experiment within this thesis provided evidence for the impact of either listening demand or the importance of successful comprehension on cardiovascular reactivity influenced by the withdrawal of the parasympathetic nervous system.

Taken together, the research reported in this thesis highlights the importance of a holistic evaluation of the physiological correlates of effortful listening guided by psychophysiological theories and motivation science. The experiments in this thesis outline a novel comprehensive approach towards the quantification of listening effort. The results highlight the importance of motivational factors and promote the perspective that both listening demand and fluctuations in the motivation to listen determine listening effort, quantified by sympathetic myocardial activation. In the future, incorporating empirically supported measures of listening effort into audiology might improve the quality of hearing assessments and the calibration of hearing aids.

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List of Acronyms.

ANS	Autonomic Nervous System
CgA	Chromogranin A
CV	Cardiovascular
DBP	Diastolic Blood Pressure
ECG	Electrocardiogram
EEG	Electroencephalography
ERP	Event-Related Potentials
FFT	Fast Fourier Transformation
fMRI	Functional Magnetic Resonance Imaging
FUEL	Framework for Understanding Effortful Listening
LF-HRV	Low-Frequency Heart Rate Variability
HF-HRV	High-Frequency Heart Rate Variability
HR	Heart Rate
HRV	Heart Rate Variability
IBI	Interbeat Interval
ICG	Impendence Cardiogram
LC	Locus Coeruleus
MIT	Motivational Intensity Theory
NASA-TLX	NASA-Task Load Index
PEP	Pre-Ejection Period

PNS	Parasympathetic Nervous System
rMSSD	Root Mean Square of the Successive Differences
RSA	Respiratory Sinus Arrhythmia
SBP	Systolic Blood Pressure
SC	Skin Conductance
SDRR	Standard Deviation of the R-R Interbeat Interval
SiWN	Speech in Pure White Noise Task
SiWN-Easy	A Low Demand Version of the Speech in Pure White Noise Task
SiWN-U	An Unclear Demand Version of the Speech in Pure White Noise Task
SNR	Signal to Noise Ratio
SNS	Sympathetic Nervous System
SSQ	Speech, Spatial and Qualities of Hearing Scale
WRT	Word Recognition Task

I. Theoretical Chapters

1. A General Introduction

Listening most likely feels effortless for many of us, but in certain circumstances, it can become a mentally demanding activity. Imagine trying to listen to someone talking quietly in a noisy environment, like a music concert; consider the effort it takes to filter out all the background noise to hear and process the speech. In this case, listening becomes a task requiring the allocation of mental resources and effort investment instead of a passive occurrence. This distinction between hearing as an inactive experiencing of some auditory stimuli, and listening as an active process purposefully directed toward the goal of comprehension or communication is frequently made in the research on audiology (Dimitrijevic, Smith, Kadis, & Moore, 2017; Kiessling et al., 2003; McGarrigle et al., 2014; Pichora-Fuller et al., 2016). For example, a study found that the identification of meaningful words presented in background noise demands more resources than does detecting meaningless sounds in noise or the passive experiencing of background noise (Kramer et al., 2013).

Research suggests that hearing-impaired individuals are required to expend more effort during listening in daily life, not only in demanding environments, than their unimpaired counterparts (Kramer, Kapteyn, & Houtgast, 2006). Those with hearing impairment, both with and without hearing aids, often report to audiologists that they are able to hear speech and they perform adequately in audiological assessments, but find that it is 'too hard' and tiring to listen (Pichora-Fuller et al., 2016). Over the last decade, many studies have investigated the phenomena of listening effort, finding that it may relate to feelings of fatigue; which lead to stress, absenteeism from work and risk of social isolation (Hétu, Riverin, Lalande, Getty, & St-Cyr, 1988; Kramer et al., 2006; Mick, Kawachi, & Lin, 2014). Considering that a substantial 1 in 6 people are affected by hearing impairment in the UK (Action on

Hearing Loss, 2014), it is imperative to invest research into previously overlooked factors that are associated with hearing loss, such as listening effort. Understanding listening effort could help improve quality of life in the hearing-impaired population; successfully quantifying listening effort gives rise to the opportunity to adjust hearing aid algorithms, or fitting procedures to decrease effort required for speech perception. Reducing listening effort, may have far reaching positive effects on communication, reduce stress, and decrease fatigue (Kramer et al., 2006; Nachtegaal et al., 2009).

Fairly recently, researchers started to investigate listening effort using subjective reports, cognitive tasks like dual-task paradigms and, physiological assessments including measures of neural activity and autonomic nervous system (ANS) reactivity (see McGarrigle et al., 2014 and Pichora-Fuller et al., 2016 for reviews). In these studies, findings often point to links between listening demand and various patterns of autonomic activation, in both impaired and unimpaired participants. However, a lack of consensus in what constitutes 'listening effort', and limited specificity in how ANS reactivity might reflect effort resulted in the use of a variety of different objective measures to quantify the phenomenon. This has often occasioned inconsistencies in the physiological findings. For example, in one study skin conductance (SC) increased as a function of listening demand but heart rate variability (HRV) only decreased under the most difficult listening condition (Mackersie & Cones, 2011). In another study the only increases in SC were found in the most complex listening task condition and least comprehensible signal to noise ratio (SNR), but HRV was found to decrease as a function of increasing SNR (Seeman & Sims, 2015). Additionally, other research using SNRs found no differences in SC in response to listening demand, and found that HRV only decreased in the most difficult condition, and only for participants with hearing loss (Mackersie, Macphee, & Heldt, 2015). A lack of theoretical framework might explain the incoherence in the physiological findings, leading to weak evidence in support of use of these measures as physiological quantifiers of listening effort.

One theory, which provides a comprehensive model for when and why individuals invest effort in mental tasks (such as listening), is Motivational Intensity Theory (MIT) (Brehm, 1989). Based on an energy conservation principle, MIT postulates that individuals use both the information about the demands of a task, and the importance of task success, to adjust their effort investment in tasks where the outcome is dependent on task performance (such as successful speech comprehension). In doing so, individuals ensure energy conservation by never investing more energy than required and or justified in any given task.

Most empirical evidence supporting the predictions of MIT relied on Wright's (1996) integrative approach. By incorporating Brehm's work with Obrist's (1981) active coping hypothesis, Wright predicted that effort investment in cognitive tasks (i.e., listening effort) is associated with increased myocardial sympathetic nervous system (SNS) activity. Wright's integration provided a definition of effort investment that enabled researchers to conduct empirical research on cognitive effort under the various predictions of MIT while maintaining a separation between the to-be-tested measure and the experimental manipulations. It is therefore unsurprising that most of the literature based on this approach is limited to a single branch of the ANS, the sympathetic branch. However, this may not provide a holistic view of effort-driven autonomic reactivity. There is substantial evidence, from both studies on physical effort and psychophysiological theories, that the parasympathetic branch of the ANS may be integral to regulation of cardiac activity during effort investment (e.g. Berntson, Cacioppo, & Quigley, 1991; Robinson, Epstein, Beiser, & Braunwald, 1966; White & Raven, 2014). The research in this thesis draws on empirical evidence on ANS reactivity associated with physical effort as well as on MIT (Brehm, 1989) with the aim of developing a model that enables a more systematic approach to researching the psychophysiology of listening effort.

This thesis will provide a comprehensive theory-driven analysis of the autonomic correlates of listening effort that focuses on myocardial ANS reactivity mediated by both the parasympathetic and sympathetic branches. The first chapters will focus on reviewing the current prevalent theories on effort investment. Particularly focusing on Brehm's MIT, and other comparable theoretical models that draw on energy conservation and motivational considerations in their approach to understanding mental effort. Subsequent chapters will present theoretical and empirical evidence on the ANS, with emphasis on sympathetic and parasympathetic activity during effort investment. Following sections will cover the current research on listening effort, with emphasis on the various measures used to assess it thus far. Following these theoretical chapters, detailed methodology and rationale for the use of particular measures employed in the research within this thesis will be presented. the Finally, a series of studies conducted within the context of this PhD that address the predictions of MIT in relation to the autonomic correlates of listening effort will be disseminated.

2. Physiological Theories of Mental Effort

In order to understand effortful listening, it is first necessary to explore psychological theorisation on mental effort. Motivational intensity theory (MIT) is a psychological theory about the determinants of effort that provides a similar definition of effort to that which is presented in the recent consensus article on listening effort, the Framework for Understanding Effortful Listening (FUEL) (Pichora-Fuller et al., 2016): the allocation of mental resources to a goal directed task. At the centre of MIT is the fundamental principle that a person's energy resource is limited, so individuals should by nature aim to conserve it where possible. To ensure the economical distribution of resources individuals should use the information about a given task to adjust their effort investment according to certain parameters: the task difficulty and the importance of task success. By doing so, individuals can ensure that energy is never wasted or invested without means. The following sections contain descriptions of the theories that preceded MIT, the theory itself and associated theories.

2.1. An Energy Conservation Principle

Two akin principles are at the heart of MIT: Zipf's (1950) Principle of Least Effort and Hull’s (1943) Law of Less Work. Both these theories share the fundamental notion that the overriding goal of all organisms is to conserve limited energy resources. Zipf suggested that in every task an individual carries out, the total work required is analysed as well as the potential work required in future tasks, in order to minimise total effort expenditure over time (Zipf, 1949). Hull’s too draws on an energy conservation principle; he suggested that given a choice of two tasks with equal rewards an individual would choose the least effortful option (Hull, 1943). The intrinsic need to avoid wasting resources is obvious in many real-world situations: when one avoids a footpath and instead walks over a lawn to reach a destination or takes the lift as opposed to the stairs.

Research provides some evidence for the innate principle of energy conservation in demonstrating that practicing a task causes individuals to learn how to complete the given task more efficiently to conserve energy. In studies that used oxygen consumption or muscle force as measures of energy consumption found that with practice individuals display more efficient gait patterns (Sparrow & Newell, 1994) and show more refined co-ordination and control over movement (Lay, Sparrow, Hughes, & O’Dwyer, 2002) to reduce energy expenditure. These studies suggest that after practicing a task, individuals will adopt the most energy conserving method to attain task goals. An alternative study by Kool and colleagues (2010) aimed to extend the current research base from physical energy to cognitive energy and in doing so demonstrated that individuals select the less effortful of two competing tasks if both lead to the same reward. The researchers showed that individuals displayed an avoidance towards cognitive demand in a variety of mental tasks and suggested that this provides evidence for the energy conservation principle (Kool, McGuire, Rosen, & Botvinick, 2010).

However, there is evidence to suggest that individuals do not always perform the least effortful of tasks, which contests the energy conservation principle. There is a breadth of research available that highlights instances where individuals actively seek out the most cognitively demanding tasks (for example, work on the need for cognition by Cacioppo & Petty, 1982). In the need for cognition research, the desire for conservation of effort is offset by the individual incentives and motivations. This researcher highlights the importance of the effort-reward trade off that underpins behaviours, emphasising the idea that it is not only the desire for conservation that determines behaviour but a multitude of motivational factors. Further research that adopted a motivational perspective towards the energy conservation principle provides additional confounding evidence against the dominance of energy conservation. Richter conducted a series of studies that measured exerted force in handgrip tasks. The findings indicated that although force increased with the demands of the task, individuals consistently over-invested effort above that which was required for task success (Richter, 2014), and did not disengage effort in impossible task conditions (Stanek & Richter, 2016). These studies provide evidence against the energy conservation principle because individuals invested more energy than necessary and even invested when task success was impossible. However, the results do still indicate the importance of task demands in the adjustment of behaviour, which is a key principle of Motivational Intensity Theory.

2.2. Precursors to Motivational Intensity Theory

Most psychological theorising on effort refers to a limited capacity of resources that should be consumed efficiently. Kahneman's (1973) model of attention (or effort as it used synonymously) assumes a central processor evaluates the demands of a given activity and allocates attentional capacity accordingly. According to this model, effort increases steadily with increasing demands of a primary task, when the supply of effort does not meet these demands; task performance falters or fails entirely. He concluded that many tasks can be completed concurrently so long as the total attention required does not exceed the limited capacity (or effort) available (Kahneman, 1973). This model provided a theoretical basis for much of the research that has used behavioural methods to measure listening effort. For example, dual-task measures of listening effort draw on the assumption that processing resources are limited and shared among concurrent tasks. In a dual-task paradigm, an individual is asked to perform two tasks simultaneously, a primary listening task of interest and a secondary cognitive task. The task performance is compared between single-task conditions (primary task is administered alone and secondary task administered alone) and the dual-task condition (both the primary and secondary tasks are administered); listening effort is quantified as the change in performance between the single secondary task and the dual-task (Gagné, Besser, & Lemke, 2017).

In a similar vein, Norman and Bobrow (1975) coined the term 'Resource Limited Processes'; simply a process can be limited by the amount of available processing resources (e.g. effort). If one allocates too little effort due to competition from other processes for the pool of available resources, poorer task performance will ensue. Whereas, an increase in applied resources will benefit performance. Any process that displays this relationship between processing resources and performance is

Resource Limited (Norman & Bobrow, 1975). Interestingly, Norman and Bobrow made a distinction between the above type of process and a 'Data Limited Process'. Unlike resource limited, processes in which performance is solely dependent on the quality of the information are data limited and left unaffected by the further allocation or removal of mental resources. Listening effort likely encompasses aspects of both these processes. It is data limited to the extent that environmental noise can reduce the perceptibility of auditory information, and resource limited to the extent that the central processing of auditory information requires top-down input from limited cognitive resources.

2.3. Jack Brehm's Motivational Intensity Theory

If the principal aim is to conserve energy, then individuals need to adjust their effort investment in a given behaviour according to the level of demand that is required to attain the goal. Effort investment (i.e. listening effort) increases as a function of task demand (i.e. the difficulty to understand speech). This ensures that the individual uses only the effort required by the task difficulty and avoids over investing effort in an easy task. Brehm considers this 'actual motivation'; the amount (of effort) a person invests to attain a goal. Brehm also proposed a boundary on the demand-effort relationship: effort should only be a function of task demand if task success is (1) possible and (2) the required effort is justifiable. This means that effort will increase with task demand up until the point that the task remains possible, ensuring that energy is not wasted by investing effort in tasks where the goal is unattainable. Furthermore, individuals should only invest effort when goal attainment is justified; if the costs of effort investment outweigh the importance of task success then one should remove effort, to avoid wasting resources. Brehm considers this 'potential motivation'; the amount (of effort) a person would be willing to invest to attain a goal. These are the predictions of MIT when task demand is clear to the individual. In situations where the demands of a task are unclear, the importance of success becomes the sole predictor of effort investment; this ensures that individuals do not waste energy resources on an unjustifiable task. Effort investment (i.e. listening effort) increases as a function of the importance of task success (i.e. the importance of successful speech comprehension). See Figure 1 for a visual representation of the theoretical predictions.

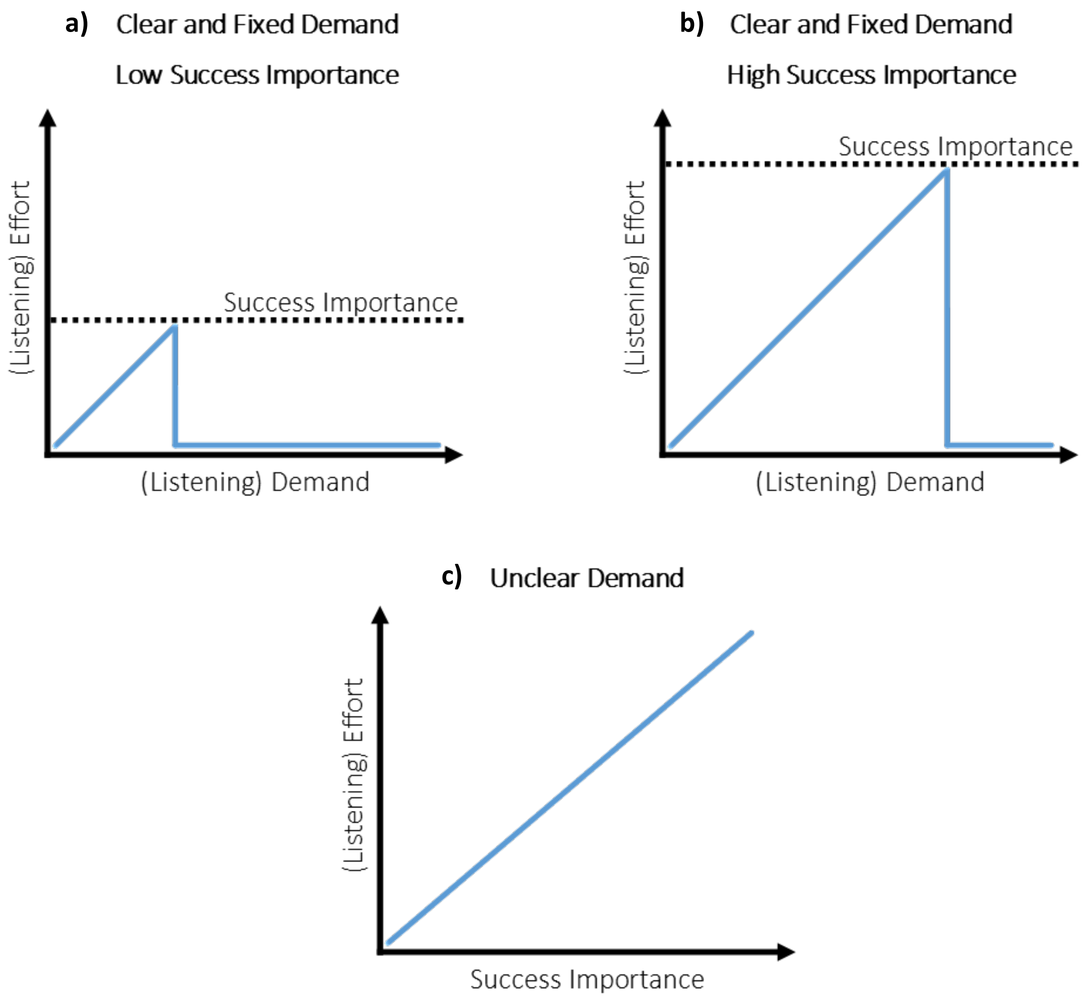

Figure 1.

Three graphs demonstrating the predictions of Motivational Intensity Theory (MIT). Graphs A and B demonstrate the predictions of MIT for listening tasks with a known performance standard or a clear and fixed listening demand level. In these tasks, listening effort occurs as a function of *listening demand while success is both possible and the effort investment is justified, which is determined by the importance of success. Graph C demonstrates the predictions of MIT in listening tasks where the performance standard is not known (an unclear demand level); in these tasks listening effort occurs as a function of the importance of task success.*

2.4. Alternative Theories on Effort

Drawing on the work of Kahneman, Norman and Bobrow, and Broadbent, Hockey proposed a Compensatory Control Model of Effort (Hockey, 1997). A main theme of this model was the emphasis on the motivational control of action: control of goals in directed behaviour is self-regulated through a cost-benefit analysis between the use of effort and goal value; the regulation then results in costs manifested in the expenditure of mental resources. Hockey suggested that not all processes are required to undergo this analysis, only when a change in task load requires intervention. Effort regulation follows either a 'low level' path whereby task demands govern the allocation of effort. On the other hand, an 'upper level' path which provides optional modes of effort regulation according to various motivational factors such as, the goal value, fatigue, or affective states. Some years later Hockey expanded on his first model and presented the Motivational Control Theory of Cognitive Fatigue (Hockey, 2011). In this model, he suggested that fatigue was a by-product of extended use of high effort control strategies that reflected conflict between many goals for the control of action. Of interest, the model predicts that the effect of fatigue should be greater when the current task goal is relatively low in the goal hierarchy and strong competing goals are present.

Cognitive Energetics Theory (Kruglanski et al., 2012) built on the core principles of MIT and suggests that effort represents a process by which a driving force (potential motivation as defined in MIT) matches a restraining force (task demands and or resource capacity) to enable goal pursuit. The model postulates that as long as the functionally interchangeable elements of the driving force (goal importance and the resource pool) meet or exceed the functionally interchangeable elements of the restraining force (alternative goals, task demands and the need conserve resources) then goal attainment is possible. The larger the driving force in comparison to the restraining force the more likely that one will achieve goal attainment.

3. The Physiology of Effort

Often psychological theories on effort or energy make ambiguous links between effort investment and physiological reactivity. For example, in Kahneman's (1973) model of attention he suggested that variations in physiological arousal should accompany variations in effort. In doing so, he inferred that the limited capacity of cognitive resources and arousal in the autonomic nervous system (ANS) must be closely linked. The sympathetic and parasympathetic branches react to environmental stimuli in a variety of ways, to control the appropriate function of the ANS. For example, SNS activity leads to increased sweating and pupil dilation whereas, PNS activation leads to greater variability in heart rate and pupil constriction.

3.1. The Sympathetic Nervous System

Paul Obrist proposed a physiological distinction between 'active' coping (an effortful action by an individual on their environment) and 'passive' coping (the unconscious or submissive response to some environmental situation). He suggested that the two are associated with distinct cardiac outcomes. Active coping is akin to the fight-or-flight response and occurs in situations where there is some possibility of escape from a given activity and or some degree of actual or perceived control; it is characterised by beta-adrenergic stimulation of the heart (Obrist, 1981).

By integrating Brehm's MIT with Obrist's (1981) active coping approach, Wright provided researchers with a reliable method to quantify effort. Wright defined effort mobilisation in active coping (wherein task performance determines task success) as being reflected in cardiovascular reactivity, specifically beta-adrenergic driven sympathetic activity (Wright, 1996). Since this conceptualisation, a breadth of supporting evidence for MIT's predictions has emerged in hundreds of studies on a diverse range of topics. Examples of its application include: the influence of implicit affect (Chatelain, Silvestrini, & Gendolla, 2016); the impact of high self-focused attention (Silvia, McCord, & Gendolla, 2010); personality effects (Richter, Baeriswyl, & Roets, 2012; Silvia, Eddington, Beaty, Nusbaum, & Kwapil, 2013); the impact of depression (Brinkmann & Franzen, 2013; Brinkmann, Franzen, Rossier, & Gendolla, 2014); and a single paper on listening effort (Richter, 2016b). Additionally, a number of studies have been conducted on how manipulations of the various predictions of MIT like the moderating effect of reward (Richter & Gendolla, 2009b) influence effort. These studies are characterised by their use of systolic blood pressure (SBP) and pre-ejection period (PEP) as indicators of beta-adrenergic impact on the heart. Initially, researchers used SBP as an indicator of sympathetic cardiovascular activity. SBP is the highest amount of arterial pressure during a heartbeat. It is strongly dependant on the force of myocardial contractility, which is primarily affected by sympathetic beta-adrenergic output to the myocardium.

However, the accuracy of interpretation of beta-adrenergic influence when using SBP is not faultless. Peripheral resistance, which is mediated by either SNS or PNS control, causes increases in SBP independent of myocardial influence (Levick, 2003). Researchers have since employed PEP, a more direct measure of beta-adrenergic influence, to quantify effort; PEP is directly dependant on the force of myocardial contraction. There is substantial empirical evidence to suggest that PEP is a sensitive measure of beta-adrenergic sympathetic activity (Newlin & Levenson, 1979). Studies found that beta-adrenergic receptor agonists (such as adrenaline) lead to significant decreases in PEP (Mezzacappa, Kelsey, & Katkin, 1999). In a similar vein, administering a beta-adrenergic blockade using antagonists (beta-blockers) prevents decreases in PEP from occurring (Cacioppo et al., 1994).

If one adopts Wright's (1996) integrative perspective, that beta-adrenergic activity reflects effort investment, then PEP is the best and most accurate way of measuring effort-driven physiological reactivity. PEP is defined as the time interval between left-ventricular excitation and the opening of the aortic valve, these events can be seen clearly as the Q point on an ECG trace and the B point on an impendence cardiograph (ICG). With increased beta-adrenergic impact, the heart contracts more forcefully, reducing the time taken for the aortic valve to open following left-ventricular depolarisation thus shortening the length of PEP.

3.2. The Parasympathetic Nervous System

Since the current literature on MIT has almost exclusively focused on the SNS as an indicator of effort investment, it has excluded the other branch of the ANS, the PNS; which could play an integral role in the regulation of cardiac activity during effort investment. The influence of the parasympathetic nervous system (PNS) is widely recognised in physical effort research. It is the consensus that PNS withdrawal also drives the increase in cardiac activity which is experienced during physical activity, as well as SNS activation (White & Raven, 2014). More specifically, a shift in ANS balance between PNS dominance to SNS dominance regulates cardiac activity during effort mobilisation in physical tasks.

During physical rest, the PNS dominates cardiac control, facilitating a resting heart rate of 60-75bmp (Gordan, Gwathmey, & Xie, 2015). The parasympathetic nervous system innervates the heart via the vagus nerve, and releases acetylcholine, the main neurotransmitter of the PNS. Acetylcholine then binds to specific receptors in the cardiac muscle cells, which produces inhibitory cardiac effects such as, decreased heart rate, reduced cardiac contractility and conduction velocity at the atrioventricular node. At low intensity exercise, a reduction in PNS activation mediates initial increases in cardiac activity; this mechanism is referred to as parasympathetic withdrawal, the removal of the inhibitory parasympathetic influence on the heart. As exercise intensity increases to a moderate level, further withdrawal of the PNS and increased influence of the SNS modulate increased cardiac activity. At high intensity exercise, further increases in cardiac activity are dominated by increases in SNS activity as the PNS is totally withdrawn (Robinson et al., 1966; White & Raven, 2014). It is probable that the regulation of cardiac activity in mentally demanding tasks is comparable to that which occurs in response to physical demand. Drawing on models that suggest that ANS activity observed during the performance of demanding tasks reflects responses that were once adaptive in ancestral physical situations (Boyce & Ellis, 2005; Nesse, Bhatnagar, & Young, 2010; Obrist, 1981), it is hypothesised that the ANS system does not differentiate between physical and cognitive tasks. The idea that both branches are of paramount importance is reflected in Berntson's (1991) modes of autonomic functioning. The model suggests that the myocardium has multiple modes of control that are activated by various changes in the balance between parasympathetic and sympathetic influence. Berntson suggested that changes in cardiac activity are modulated either by reciprocal coupling of the PNS and SNS, non-reciprocal coupling which comprises co-activation or inhibition of both branches, or uncoupled activation of a single branch (Berntson et al., 1991).

A number of current empirical articles on listening effort, which employed measures of parasympathetic activity such as HF-HRV (Mackersie & Calderon-Moultrie, 2016; Mackersie et al., 2015), relied on the above conceptualisation.

However, none of the existing studies measured the joint effects of SNS and PNS activity in one organ, which is important as SNS activation is not equally distributed throughout the body. In order to gain a holistic view of ANS balance during listening, the measure of PNS and SNS activity at a single organ is required. Heart rate variability in the respiratory frequency band (respiratory sinus arrhythmia: RSA) is a valid indicator of cardiac parasympathetic activity (Berntson, Cacioppo, & Quigley, 1993). Parasympathetic cardiac input is regulated by the efferent vagus nerve, which affects heart rate related to respiration. After an individual breathes in heart rate increases and after they exhale it decreases. At rest, when parasympathetic activity is high, the heart both accelerates and decelerates in accordance with breathing rate, resulting in high variability between each heartbeat. Whereas, during effort investment heart rate and respiration rate increase, decreasing HF-HRV and implying decreased parasympathetic activity. Research finds that RSA decreases under conditions of high task demand (Capa, Audiffren, & Ragot, 2008). Also, RSA has been validated as a measure of PNS reactivity in pharmacological blockade studies (Berntson et al., 1997; Berntson, Cacioppo, & Quigley, 1994). Combing complementary measures of cardiac PNS and SNS activity using PEP and RSA will provide valuable information for the quantification of effortful listening that will add significantly to the current literature.

4. An Outline of Effortful Listening

The concept of listening effort likely emerged as a self-reported subjective state, described by hearing-impaired individuals as a feeling of having to ‘’work hard’’ to cope with speech comprehension (Pichora-Fuller et al., 2016). Although listening may feel like an effortless activity for many of us, there are many complex cognitive processes involved in the attending to, processing and understanding of speech, which become much more demanding if your auditory system is impaired. The phrase, *"we hear with our ears but we listen with our brains"*, is often referenced to in audiology and cognitive hearing science (Pichora-Fuller et al., 2016). This is because listening for the purpose of speech comprehension relies on a combination of both bottom-up processes in the ear itself and top-down processes like attention and memory. To understand hearing loss and its effects on an individual that span further than an audiological or acoustic profile, such as effortful listening, it might first be useful to examine how speech comprehension happens.

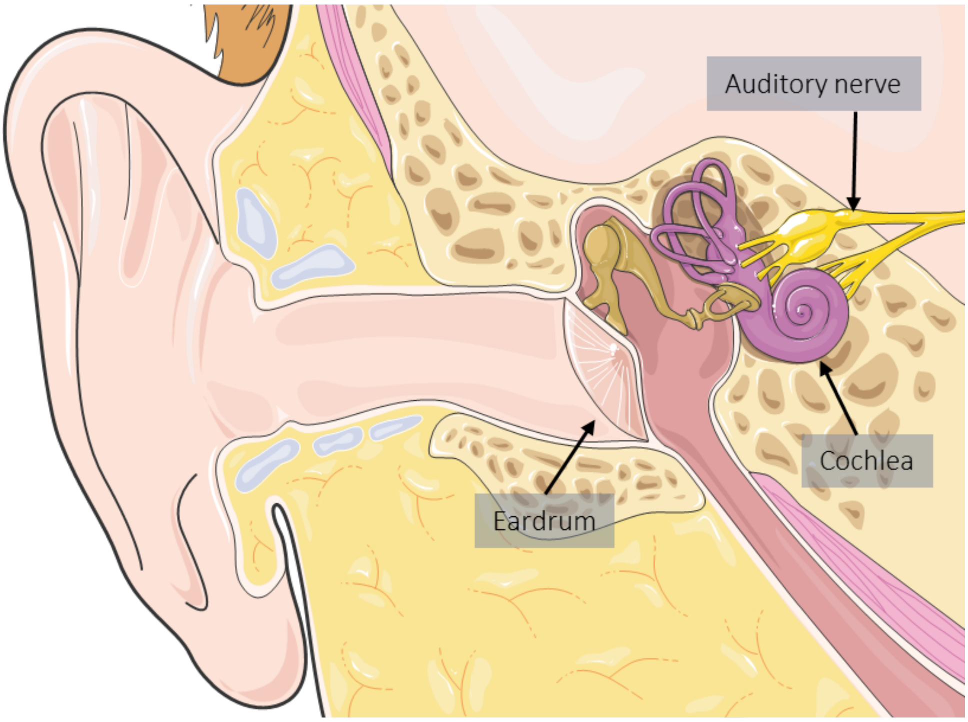

Figure 2.

The peripheral auditory system. The outer ear, which collects the sound wave; the ear drum, which transforms the sound to vibration; the cochlea in the inner ear, which transforms the vibrations into electrical signals; and the auditory nerve, which generates action potentials. Figure 2 was modified from Servier Medical Art, licensed under a Creative Common Attribution 3.0 Generic License.

4.1. Bottom-Up and Top-Down Mechanisms in Auditory Processing

4.1. I. Signal Transduction. The shape of the outer ear, the part that is visible can see when looking at a person, functions as a funnel to gather sound and direct it down the ear canal to the tympanic membrane (or eardrum). It is there that the transformation of sound into vibration occurs. The small bones of the middle ear, named the ossicles, transmit the vibrations to the inner ear. The inner part contains the fluid filled spiral-shaped cochlea, where the vibrations stimulate movement in the fluid. This movement causes the basilar membrane, a structure containing sensory hair cells (the organ of Corti), which runs along the coil of the cochlear, to move as a wave. The different sections of the basilar membrane respond to different frequency characteristics of sound waves. As the waves travel down the membrane, they peak at the relevant part of the membrane that responds to the frequency of the original sound stimulus. This process causes the hair cells in the organ of Corti to excite at this specific location, these hair cells allow for the vibrations in the basilar membrane to be translated into electrical impulses that can be detected by the auditory nerve.

One could consider this bottom-up process as *'hearing'*; it occurs in the auditory periphery and constitutes the transducing of auditory stimuli into physiological information (Edwards, 2007). See Figure 2 for a diagram of the auditory system.

4.1. II. Central Processing. The spike train of electrical signals produced in the cochlea travels down the auditory nerve along the auditory pathway to the brain. The role of the auditory pathway and cortex is complex; involving signal decoding in terms of auditory characteristics like pitch, rhythm, temporal and spatial information, comparing to stored auditory information and, the attentional control or prioritising of auditory input. The auditory cortex is suggested to be arranged in a functional hierarchy for the successful comprehension of speech, the primary cortex is sensitive to the acoustic characteristics of speech whereas higher order temporal and frontal regions take on further processing such as, comparing to stored auditory information for speech intelligibility (Davis & Johnsrude, 2003). Signal transduction and central processing in order to understand auditory information is even more challenging and complex in adverse listening situations. These adverse listening conditions are typical of daily life; such as conversing at a party or, listening to a speaker in a noisy lecture hall. In these instances, the brain needs to separate the important auditory information from the background noise, in order to prevent sensory overload. For example, Bregman's (1990) Auditory Scene Analysis (ASA) is a proposed model for how the auditory system groups sounds coming from the same source, and segregates the components coming from a different source. ASA involves the grouping different sounds into distinct streams, in order to cope with speech perception when the listening situation involves sounds from numerous competing sources. The grouping is based on the similarities and differences in frequency and temporal acoustic features over time. This type of grouping into distinct auditory streams is an example of the well-known 'cocktail party effect': the remarkable ability to listen to a particular voice in a situation with multiple competing talkers and background noise (Cherry, 1953).

Cognitive processes facilitate the central processing of auditory information, such as working memory. Working memory capacity enables individuals to temporality hold information in their memory capacity for later processing. Research suggests that speech perception in noise is related to individual differences in working memory ability (Millman & Mattys, 2017; Hoi Ning Ng, Rudner, Lunner, Pedersen, & Rönnberg, 2013). Relatedly, research provides evidence for the association between speech perception abilities in noise and inhibition capacity; with poorer inhibition related to poorer speech perception in background noise (Janse, 2012).

Furthermore, there is strong evidence for the multisensory perspective of auditory processing; central processing of acoustic information in the auditory cortex is likely complemented by visual cues. A strong example of this is the McGurk effect, wherein a voice speaks a particular consonant, dubbed with a face articulating another consonant, resulting in a multisensory integration that affects how the sound is heard by the listener (Mcgurk & Macdonald, 1976). For example, a voice speaking the consonant /b/ dubbed onto a face articulating /g/ frequently results in the perception of the sound /d/; demonstrating the audio-visual integration that occurs in speech perception (Macdonald & McGurk, 1978). Further evidence of this multisensory integration comes from neuroimaging studies. Calvert's (1997) research found that normal-hearing individuals, when watching a face silently articulating speech, show auditory cortex activation in the absence of any sound. As well as this, speech perception is improved when audio-visual stimuli is present, as opposed to auditory only (Calvert et al., 1997). This provides evidence for the benefit of multisensory integration for speech perception and highlights the use of numerous cortical and sensory resources in speech processing.

Relatedly, the articulatory motor cortex (involved with lip and tongue control during speech production), shows increased excitability during speech perception (Watkins, Strafella, & Paus, 2003), particularly when perceiving speech in noise (Nuttall, Kennedy-Higgins, Hogan, Devlin, & Adank, 2016). Furthermore, when articulatory motor cortex activity is temporarily disrupted using inhibitory brain stimulation techniques, speech perception involving identification of speech sounds articulated by the lip is hindered (Möttönen & Watkins, 2012).

Cognitive processes and neural integrations clearly compliment auditory signal processing to make sense of speech. These top-down cortical and cognitive processes, including auditory, visual and motor brain areas, as well as working memory, inhibition and attention, go beyond the *'hearing'* of speech, they are imperative for successful *listening*, comprehension and communication (Rönnberg et al., 2013). It is thus likely that these systems are affected by degraded auditory input, by having to allocate more cognitive resources or brain areas to facilitate speech perception.

4.1. III. Impaired Auditory Processing. Varying damage to parts of the auditory periphery result in different forms of hearing loss. For example, sensorineural hearing loss results from missing or damaged hair cells within the cochlea and the level of severity can vary among individuals. Whereas, any problem in the middle or outer ear causes conductive hearing loss, which results in sound waves being incorrectly conducted through the peripheral auditory system. Hearing aids alleviate the symptoms of impaired hearing by amplifying sounds so that they are more perceptible to the damaged auditory system. Clearly, the approach to facilitating hearing for those with impairment is to address the compromised bottom-up hearing processes. However, the auditory periphery is just half of a wider system involved in the processing of auditory information. As evidenced in the previous section, the processing of degraded speech, due to either impairment or environmental noise, also requires top-down involvement.

Impaired auditory processing is reported to make listening more effortful for the individual, particularly in highly demanding environments, because listeners need to use more mental effort to attend to the sounds, comprehend and possibly respond to them (Desjardins & Doherty, 2013; Nachtegaal et al., 2009; Pichora-Fuller et al., 2016). It has been suggested that this effort is used by the cognitive system having to work harder 'filling in the blanks' in missed auditory information by accessing working and long term memory to maintain understanding (Edwards, 2007; Rönnberg et al., 2013). The Ease of Language Understanding model (ELU) proposed by Rönnberg (2013) and colleagues provides one explanation for how the brain manages to use cognitive and cortical resources to separate important auditory information from background noise. They suggest that phonological information is quickly and automatically grouped together (like the ASA model) and represented in a short-term buffer, which they refer to as RAMBPHO. When the listening situation is ideal, the buffer input matches enough phonological characteristics stored in the brain's mental lexicon. But, when the listening situation is poor, due to impaired hearing or background noise, cognitive resources are used to support successful speech comprehension. These resources include, working memory, phonological long-term memory, and semantic long-term memory, which all work to infer the missing auditory input (Rönnberg et al., 2013). It is the perspective of this thesis that drawing on these cognitive resources requires increased mental effort.

4.1. IV. Hearing Aids and Listening Effort. There is little evidence to suggest that hearing aids, although useful in the amplification of the sound, help to reduce the experience of listening effort in impaired individuals (see Ohlenforst et al., 2017 for a recent systematic review). The notion that hearing aids do not alleviate effort might provide some explanation for why adherence to wearing them is low (Aazh, Prasher, Nanchahal, & Moore, 2015; Maidment, Barker, Xia, & Ferguson, 2016). For hearing aids to be an effective solution, they must address problems beyond the amplification of sound.

The ear does not only perform a simple frequency analysis of auditory information; it performs complex nonlinear signal processing. The hair cells in the cochlea do not only vibrate the parts of the basilar membrane to which they are attached, but also modulate movement at other locations (Lesica, 2018). Therefore, sounds entering the ear undergo non-linear processing, which creates cross-frequency interactions. These interactions allow a healthy ear to create distortion products from interactions between different frequencies present in any auditory input. These distortions create movement of the basilar membrane and corresponding auditory nerve activity. The frequency interactions in the healthy ear also enable suppression of movement at parts of the basilar membrane; which facilitates frequency tuning to dominant sounds in noisy environments. Because these cross-frequency interactions are dependent on hair cells that cause basilar membrane movement, they are impacted by hearing loss (Lesica, 2018). Hearing aids cannot mimic the non-linear cross-frequency analysis of auditory information, therefore the neural signals sent to the brain are no longer enough for speech perception in noise (Lesica, 2017, 2018).

Hearing aid signal processing may also produce unwanted artefacts by distorting the auditory scene, producing audible artefacts, or distorting the target signal waveform (Lunner, Rudner, & Rönnberg, 2009; Stone & Moore, 2004, 2008). These side effects of hearing aids may further burden mental and cognitive resources. Lunner and colleagues (2009) suggest that individual's working memory capacity may impact on how effective hearing aids are in improving speech perception and listening effort. For example, hearing aids with intelligent noise reduction algorithms often produce unwanted audible distortions; which may consume working memory resources, and those with greater working memory capacity may benefit from this process, but those with lower capacity may not (Lunner et al., 2009). This is especially important as hearing loss prevalence increases with ageing, and for older adults often cognitive functioning is reduced.

Listening for the purpose of successful speech comprehension is clearly a complex cognitive and physiological process that demands effort. This listening effort is thus elevated when one must cope with both the demands of a noisy environment as well as impaired auditory processing. To understand the widespread effects of hearing loss, particularly the excessive use of cognitive effort to overcome impairment, it is imperative to be able to both define and quantify listening effort.

4.2. Defining Listening Effort

With growing prevalence of the listening effort phenomena, both reported in complaints from hearing-impaired individuals to audiologists and in empirical studies, researchers extended the conceptualisation of listening effort. The concept developed from perception of sounds in the auditory periphery to considering the cognitive or energetic processes underpinning it. The Framework for Understanding Effortful Listening (FUEL) provides a definition of listening effort that is similar to that adopted by MIT: (Listening) effort is defined as the deliberate allocation of mental resources to overcome obstacles in pursuit of a goal (i.e. successful speech comprehension) when carrying out a (listening) task (Pichora-Fuller et al., 2016). This definition along with preceding conceptualisations possess a unifying emphasis on listening effort as resource (cognitive, mental or energetic) allocation towards auditory stimuli (Bess & Hornsby, 2014; Hicks & Tharpe, 2002; McGarrigle et al., 2014; Picou, Ricketts, & Hornsby, 2013) as opposed to a subjective perception of effort. The empirical evidence supporting this idea thus employed measures to capture the nature of listening effort as resource investment e.g. dual-task paradigms and physiological mobilisation, both of which will be discussed in the following paragraphs. Prior to the recent consensus article, *The Framework for Understanding Effortful Listening (FUEL) (Pichora-Fuller et al., 2016)*, there was lack of clarity regarding the theoretical basis of listening effort, as indicated by McGarrigle et al (2014). McGarrigle (2014) highlighted the fact that interchangeable definitions described a seemingly similar construct (e.g. cognitive load or listening effort). Moreover, due to the lack of consensus regarding the underpinnings of effort in listening, the existing literature comprises several different approaches to measurement. McGarrigle’s (2014) article emphasised the contradictory findings from the various measures, with subjective reports of listening effort often proving to be unrelated to objective measures. For example, self-reported listening effort was found to be uncorrelated with physiological effort indexed by the pupil response (Zekveld, Kramer, & Festen, 2010), or skin conductance response (Francis, MacPherson, Chandrasekaran, & Alvar, 2016), or with dual-task measures of listening effort (Gosselin & Gagné, 2011). Although consensus on the quantification of listening effort seems to be lacking, there is an agreement that the sustained effort required for listening leads to further health-related concerns, including chronic fatigue (Pichora-Fuller et al., 2016; McGarrigle et al., 2014).

5. An Outline of Hearing Fatigue

Research suggests that sustained effort investment in listening gives rise to increased levels of subjective fatigue within the hearing-impaired population (Edwards, 2007; Zekveld, Kramer, & Festen, 2011). This postulation ties in with the definition of listening effort as a deliberate allocation of mental resources; fatigue emerges in response to auditory activities that demand a high level of sustained effort and consequential mental resources. Hockey's (2011) motivational control theory of cognitive fatigue suggested that the experiencing of fatigue is an adaptive function. It serves as a way for us to monitor current resource investment by evaluating the effort-reward relationship. If investing effort in a given listening activity does not lead to a sufficient reward, then one should experience decreased motivation for the task. The effort-reward relationship may also need evaluating if there is a reduction in the efficiency or availability of mental recourses (Gergelyfi, Jacob, Olivier, & Zénon, 2015), which could be due to the extended use of highly effortful control strategies managing conflict between competing goals (Hockey, 2011). For example, maintaining comprehension of speech in a noisy environment where competing sounds attract attention. In this situation the demand for resources is high and fatigue results from sustained attempts to maintain the primary goal under threat from environmental or task factors and motivational predispositions such as, the control of action, the innate need to conserve resources, or emotional valence (Hockey, 2011). In the literature hearing fatigue has typically been measured using three methods, self-reports, performance decrements during listening, and physiological reactivity. The next paragraphs will succinctly present the state of the current literature and discuss whether these methods can quantify hearing fatigue and consider its origins.

5.1. Measuring Hearing Fatigue

5.1. I. Self-Reports. The hearing-impaired population conveyed hearing fatigue in self-reports that addressed the feeling of tiredness or exhaustion resulting from effortful listening in everyday life. For example, those with impaired hearing report increased fatigue during daily life than those without impairment (Alhanbali, Dawes, Lloyd, & Munro, 2017). Further qualitative research then revealed the severity of their fatigue-related complaints. For example, individuals with hearing loss report more frequent absenteeism due to mental distress arising from 'fatigue', 'strain' and 'burn- out' (Kramer et al., 2006), and increased need for recovery after work that is augmented by degree of hearing impairment (Nachtegaal et al., 2009). These studies suggested that working life for the hearing impaired is highly demanding, due to having to cope with both the general workload and their hearing impairment that demands constant effort to communicate effectively. Hétu et al (1988) described similar findings with hearing-impaired workers reporting the need for increased attention and effort in listening, leading to amplified stress and fatigue. The research also observed increased anxiety and social isolation in hearing-impaired individuals, due to being too fatigued to engage in normal activities (Hétu et al., 1988). Furthermore, hearing fatigue extends to all persons affected by hearing loss, with older adults at risk of fatigue induced social isolation (Kramer, Kapteyn, Kuik, & Deeg, 2002) and young children being at risk of hindered development in school due to fatigue (Hornsby et al., 2017). The above research measures hearing fatigue subjectively, as a mood state, a feeling of exhaustion and unwillingness to employ effort, due to increased mental demands. However, other research found no differences between those with hearing-impairment and normal hearing on subjective measures of well-being, fatigue or recovery (Wagner-Hartl & Kallus, 2018). It may be useful to employ a more objective measure of fatigue during laboratory-based research that is less sensitive to confounding variables such as, individual differences in introspective abilities, understanding and interpretation of self-reports, or response bias.

5.1. II. Behavioural Measures. Decrements in listening task performance have been suggested to indicate a form of mental fatigue, referred to as cognitive fatigue, that occurs when an individual withdraws effort from a highly demanding listening situation to avoid the use of limited mental resources (Bess & Hornsby, 2014; Hornsby, Naylor, & Bess, 2016). Hornsby (2013) employed a dual-task paradigm that evaluated word recognition, recall, and response time as objective measures of fatigue in hearing-impaired individuals in aided and unaided states. Over the duration of the dual-task, both word recognition and word recall remained stable irrespective of hearing aid use, but participants without hearing aids were significantly slower in responding over the time course of the task. The study interpreted the slower reaction times as evidence for listening induced fatigue, and suggested that hearing aids may reduce susceptibility by alleviating task demands and reducing listening effort (Hornsby, 2013). In another study, children with hearing loss produced significantly longer reaction times than their peers with normal hearing did (Hicks & Tharpe, 2002), which could be interpreted as a fatigue-related decrement in performance due to increased listening demand. The increase in demand during listening may cause individuals to need to invest more time in processing the auditory input, leading to slower response times. The increased time spent processing the auditory information would then lead to increased fatigue.

However, although behavioural measures might be more objective than self-reports, variables like boredom or motivational factors (e.g. attractiveness of a given listening task) may drive performance decrement irrespective of fatigue (Hockey, 2011). An additional caveat arises in the ambiguous evaluation of performance. Individuals can maintain a high-performance standard in both easy and difficult tasks, depending on the value of task success, but this might not necessarily mean that maintaining adequate performance in the difficult task was not fatiguing. Furthermore, confounding variables may mask the severity of performance decrement. For example, individuals may be able to sustain the primary task goal while surrendering performance in other domains (e.g. successful comprehension at the expense of efficiency or vice versa) or maintain performance due to practice effects (Hockey, 2011; Hornsby et al., 2016). Individual differences in motivation for task success, ability for learning, or control of action may provide plausible explanations as to why behavioural and subjective measures of fatigue are frequently uncorrelated (Hicks & Tharpe, 2002; Hornsby, 2013). While a few laboratory-based listening tasks revealed efficiency related performance decrements (e.g. Hick & Tharpe, 2002; Hornsby, 2013), there are still questions to be answered in future research as to the relationship between the behavioural deterioration of performance and the accounts of acute exhaustion in the hearing impaired population (McGarrigle et al., 2014).

5.2. III. Physiological Measures. To avoid some of the caveats of behavioural measures, researchers employed alternative objective measures of hearing fatigue. These methods provide information about the physiological mechanisms associated with fatigue, for example, hormonal responses or reduced autonomic arousal reflected in pupillary reactivity. When exposed to a stressful event, the autonomic nervous system responds in a variety of ways, such as the increased secretion of stress hormones like cortisol from the adrenal gland. The stress response pathway, the hypothalamic pituitary adrenal axis, modulates cortisol and seemingly responds in parallel with the SNS in preparation for the individual to react to a given stressful event (Kramer, Teunissen, & Zekveld, 2016). Studies have employed cortisol as a potential measurement tool for chronic fatigue in the hearing-impaired population. For example, Bess and colleagues collected the salivary profiles of children with hearing loss and found that they displayed elevated cortisol levels at awakening and diminished secretion in the following 30-minutes compared to children with normal hearing (Bess et al., 2016). They highlighted that the finding was consistent with research on adults with chronic fatigue conditions and suggested that the children with hearing loss experience more vigilance at awakening in order to cope with elevated daily demands. In another study, there were no significant differences in the levels of cortisol throughout the day between children with hearing loss or normal hearing (Hicks & Tharpe, 2002). The confounding results may be because cortisol measures are highly dependent on the time of measurement, as levels decrease throughout the day. Additionally, in children, cortisol levels have been shown to be related to situational and individual factors that alter cortisol levels or the cortisol awakening response (Corbett, Mendoza, Wegelin, Carmean, & Levine, 2008; Dedovic & Ngiam, 2015)

Recently, researchers have quantified hearing fatigue using pupillometry; a popular measure in research on listening effort but has not yet gained much standing in fatigue related research. Increases in pupil size can indicate increased physiological arousal driven by the SNS, and decreases can indicate decreased physiological arousal, driven by parasympathetic nervous system (PNS) reactivity, which may indicate increased fatigue (McGarrigle, Dawes, Stewart, Kuchinsky, & Munro, 2017b). Variations in pupil size relate, in part, relate to reactivity in the locus coeruleus (LC). The LC is a nucleus within the brainstem and is the main site for neural synthesis of noradrenaline; the main neurotransmitter of the sympathetic nervous system, which innervates the pupil (along with the PNS). It has been proposed that the LC noradrenaline (or norepinephrine: LC-NE) system plays an integral role in task engagement and performance; the Adaptive Gain Theory proposed by Aston-Jones and Cohen (2005) takes this perspective. The researchers proposed output modes of the LC-NE system. The first being the phasic mode, wherein LC-NE neurons display moderate baseline activity with strong stimulus-evoked bursts of noradrenaline release; this mode supports high task engagement. Alternatively, the tonic mode is characterised by more irregular LC-NE baseline activity; this mode is associated with poorer performance and distractibility during tasks (Aston-Jones & Cohen, 2005). A third mode is proposed to be characterised by low baseline and low stimulus-evoked levels of noradrenaline; leading to reduced attention, and task disengagement (Aston-Jones & Cohen, 2005). It has been suggested that this mode, measured by changes in pupil diameter, is related to the experiences of fatigue (J. Hopstaken, 2016; J. F. Hopstaken, van der Linden, Bakker, & Kompier, 2015). McGarrigle and colleagues have conducted a series of studies investigating the fatigue related pupil response. In one study they found that young adults displayed a sharper decrease in pupil size during the second half of a difficult listening task, while performance accuracy remained stable, indicating reduced physiological arousal coherent with listening induced fatigue (McGarrigle et al., 2017b). Whereas, these findings were not corroborated in another study where there were no differences in fatigue indexed by pupillometry in school children in response to listening demand (McGarrigle, Dawes, Stewart, Kuchinsky, & Munro, 2017a); however this study used speech in noise tasks at levels which were less demanding and therefore unlikely to elicit physiological fatigue.

5.2. Defining Hearing Fatigue

It is clear that there are two important aspects of fatigue associated with effortful listening. The self-reported fatigue that individuals experience as a result of 'working hard' to understand speech in daily life, and a behavioural aspect of fatigue which presents itself as withdrawal from demanding listening situations. For the purpose of this thesis, two definitions of fatigue will be adopted and investigated in experimental studies, in order to gain a holistic picture of hearing fatigue. Firstly, subjective fatigue is defined similarly to the definition provided by Hornsby (2016) and revisited in the consensus article, *The Framework for Understanding Effortful Listening (FUEL) (Pichora-Fuller et al., 2016)*; subjective fatigue occurs an mood state, involving feelings of exhaustion, tiredness and lack of energy, or decreased motivation to continue, resulting from sustained mental effort. Secondly, the definition of objective fatigue is informed by Hockey's (2011) motivational control theory of cognitive fatigue; that the experience of fatigue (subjective) leads to a change in behaviour, such as withdrawing effort from a task to reduce fatigue and conserve resources. Hornsby et al. (2016) defined this behavioural response as cognitive fatigue; referring specifically to fatigue-related performance decrements on tasks. In this thesis, therefore, objective fatigue is defined as a behavioural response to sustained mental effort, reflected in task-related performance decrements. As will be discussed in detail in the following section, the relationship between listening effort and fatigue is not well supported by empirical evidence as of yet. As such, it is important to provide clear definitions of the aspects of fatigue hearing-impaired persons experience and invest research efforts into understanding their relationship to listening effort.

6. The Effort-Fatigue Relationship

Findings from studies on hearing fatigue currently provide unclear evidence with regard to the causal relationship between listening effort and fatigue. If, as subjective reports of hearing impairment imply, hearing fatigue occurs when individuals are required to invest extra effort to compensate for auditory processing, it would be reasonable to assume that the degree of hearing impairment might relate to the extent of fatigue caused. However, the research provides little evidence for a relationship between fatigue and degree of hearing loss (Alhanbali et al., 2017; Nachtegaal et al., 2009). These findings suggest that the relationship between listening effort and fatigue is much more complex than the simple idea that the more difficult auditory input is to understand (for example due to impaired hearing), the more effort is required and, the more fatigue is experienced. Additionally, many studies have found weak or no correlation between self-reported effort and fatigue (for examples, Alhanbali et al., 2017; Hornsby & Kipp, 2016). Further objective indicators of fatigue have also provided weak evidence for the effort-fatigue relationship, for example Hornsby (2013) found that correlation analysis showed no relationship between behavioural or subjective measures of fatigue and effort. Other research found that the various physiological indicators of effort and fatigue (pupil responses, cortisol and CgA) displayed dissimilar responses to increased listening demand (Kramer et al., 2016). One explanation for the inconsistent data could be that objective and subjective fatigue are different constructs and relate to listening effort in complex ways dependant on differences in individuals and situational factors.

The inconsistent relationship between listening effort and hearing fatigue may depend on additional motivational factors that require further research efforts to understand. For example, beyond listening demand lies the innate need for resource conservation and alterations in goal orientation (Hockey, 2011), that may influence effort investment in listening and thus hearing fatigue. Furthermore, even the demonstration that listening demand leads to increased fatigue would not be sufficient in providing evidence for an effort-fatigue relationship. As pointed out by Earle and colleagues (2015), inferring an effort-fatigue relationship from the task demand-fatigue relationship would require a separation of effort from task demands. Considering Hockey's fatigue hypothesis, increasing effort in a task can overcome the experience of fatigue, independently of task demands, due to an enhanced motivation to maintain commitment to the task goal (Earle, Hockey, Earle, & Clough, 2015; Hockey, 2013). Considering motivational factors in the research on hearing fatigue would provide researchers with a more holistic view of how the relationship between listening effort and hearing fatigue manifests.

The research, although contradictory regarding the quantification of fatigue, is consistent in proving that the manifestation of hearing fatigue and its relationship to listening effort is complex and multifaceted. The current empirical evidence for the effort-fatigue relationship is in its infancy and is too confounding to draw any definitive conclusion. However, it is clear that fatigue-related complaints are prevalent in the hearing-impaired population and they occur alongside complaints of effort. Therefore, it is important to invest new research efforts into the quantification of listening effort and hearing fatigue to understand the causational relationship.

7. Measuring Listening Effort

Researchers have employed various methods to measure and quantify listening effort with popular approaches being self-reports, dual-task paradigms or physiological measures. Initially, articles focused on the subjective reporting of effortful listening in the hearing-impaired population, to provide evidence for the phenomena of listening effort. In doing so, researchers speculated that individuals with impaired hearing needed to invest more of their cognitive resources in listening (or more listening effort) to cope with environmental demands and successfully perceive speech.

In order to find a more objective way of quantifying effort than through self-reports researchers used behavioural measures such as dual-task paradigms. These measures rely on the assumption that individuals have a limited conserve of resources that can be distributed and shared among various tasks and activities.

Based on this idea, researchers asked participants to complete two tasks simultaneously in the belief that any resources used to complete the secondary task are those left over from the primary task. The performance level on the second task would indicate the amount of 'left over' resources allocated to it, in turn representing the amount of effort or cognitive resources given to the primary task.

An alternative objective measurement of effort, which may rely on fewer assumptions about resource capacity, employed in the listening effort research is physiological reactivity. Studies that used physiology to quantify effort suggest a specific pattern of activation in the ANS is reflective of effort investment. Most of these studies have suggested that an increased listening effort response to environmental demands may be experienced by the listener as physiological 'stress' (Dorman et al., 2012; Kramer et al., 2016; Mackersie & Cones, 2011; Mackersie et al., 2015). The researchers draw on the conceptualisation that the ANS responds to exposure to a stressor through increased activity the in sympathetic branch (the fight or flight response) and decreased activity in the parasympathetic branch (responsible for maintaining resting state) (Mackersie & Cones, 2011). Arousal of the SNS and suppression of the PNS may result in objectively measurable physiological changes such as fluctuations in heart rate, blood pressure, skin conductance or pupillary responses. For example, sympathetic activation might increase heart rate and dilate the pupils whereas parasympathetic activation might decrease heart rate and constrict the pupils. This idea is consistent with the consensus in cardiovascular psychophysiology; that responses of the cardiovascular system in the anticipation and preparation for some action (such as, listening) is altered by motivational and emotional processes that are mediated by sympathetic and parasympathetic control (Obrist, 1981).

7.1. Self-Reports

As already briefly mentioned, a popular and straightforward index of listening effort is by measuring the individual's subjective perception of effort using both standardised and novel self-reports. As discussed above, questionnaires have been widely employed to assess effort in the hearing-impaired population. For example, the Speech, Spatial and Qualities of Hearing Scale (SSQ) (Gatehouse & Noble, 2004) aims to examine hearing in everyday life and has been found to be a reliable predictor of listening effort (Singh & Kathleen Pichora-Fuller, 2010), similarly the Amsterdam Checklist for Hearing and Work found that hearing impairment strongly correlated with effort in hearing (Kramer et al., 2006). Questionnaires are also useful for assessing perceived effort in experimental situations before and after manipulations of listening demand, using speech in noise for instance. Using the NASA-Task Load Index (NASA-TLX) (Hart & Staveland, 1988) individuals reported more effort when tasks involved degraded speech (Francis et al., 2016) and items assessing 'effort' and 'mental demand' showed the largest systematic increase as a function of task demand (Mackersie & Cones, 2011). A number of studies used alternative Visual Analog Scales to assess subjective effort in listening task paradigms (Kramer et al., 2016; Rudner, Lunner, Behrens, Thorén, & Rönnberg, 2012; Zekveld et al., 2011), and have found that listening demand is related to perceived listening effort.

Clearly subjective reports are useful for the identification of perceived effort investment in listening and can provide valuable information about how an individual is coping with a hearing impairment. However, using self-reports as a standardised measure of listening effort poses an array of issues. A recent article by Picou and Ricketts (2018) highlighted that subjective measures may not be valid for measuring listening effort, due to high inconsistency between subjective and objective measures (Picou & Ricketts, 2018). A general problem with self-reported measures is that one person's classification of effort may differ from that of another, as highlighted by McGarrigle et al. (2014); Larsby et al. demonstrated that older adults tend to underestimate effort in comparison to younger adults (Larsby, Hällgren, Lyxell, & Arlinger, 2005). Individual differences in definitions of 'effort' and 'demand' could also pose problems in how people may perceive and answer questions. Secondly, self-reported effort is often contradictory to evidence from other methods of measurement such as behavioural and physiological responses (Mackersie & Cones, 2011; Seeman & Sims, 2015; Zekveld et al., 2010). Highlighting that effort as a feeling and effort as deliberate investment of mental resources to overcome obstacles in goal pursuit may be functionally and measurably separate constructs. If listening effort is a resource driven process, then alternative measures may prove more suitable than those that assess a subjective construct.

7.2. Behavioural Measures

7.2. I. Dual-task paradigms. Research based on defining listening effort as a deliberate allocation of mental resources during auditory tasks, draws on the perspective that the available cognitive resources for an activity at any one time are limited. In a dual-task paradigm, a participant engages with two tasks simultaneously, a primary and a secondary task. In the listening effort literature, the primary task is typically an audiological task and the secondary task is a cognitive one. Researchers postulate that as the primary task becomes more effortful (increased listening demand) there are fewer resources remaining to dedicate to the secondary task and thus performance on this task should falter. Therefore, it is theoretically possible to use the information about secondary task performance to measure effort investment in the primary task. A number of studies employing this type of paradigm have shown that increasing the level of background noise in a listening task results in performance decline on secondary tasks; indicating that the primary task required more mental resources and thus increased listening effort

(Fraser, Gagné, Alepins, & Dubois, 2010; Sarampalis, Kalluri, Edwards, & Hafter, 2009; Seeman & Sims, 2015). Despite being used frequently to draw important inferences in the listening effort research, such as that older adults require more resources for speech recognition (Gosselin & Gagné, 2011) and that listening is less effortful when aided (Hornsby, 2013), the extent to which effort can be inferred from performance on a secondary task is questionable. For example, Hicks and Tharpe (2002) suggested that the poorer reaction times in children with hearing loss, compared to their non-impaired peers, indicated that they expended more effort. However, there were no differences in speech recognition scores between the two groups, which could indicate that task was not demanding enough to evoke effortful listening in the hearing-impaired group. However, the opposite could also be argued, in that the participants may have invested enough effort to maintain a high performance standard. It is for this reason that it is not simple to disentangle effort investment from task performance scores. A slower reaction time on the secondary (or even primary) task could be explained by other cognitive processes unrelated to resource depletion, such as task switching or inhibition both of which could cause momentary lapses in response speed (Seeman & Sims, 2015). In addition, the act of switching tasks itself may ensue unavoidable energy expenditure; this raises another important issue regarding the reliance on a number of assumptions enabling dual-tasks to be an accurate measure. The paradigm assumes that all available resources will be allocated to the primary task and any 'left over' will be used for the secondary task, without ever directly measuring the definite resources used and overlooking that many other habitual processes may consume cognitive resources. The measure also assumes that one will deliberately allocate resources to the primary task over the secondary task, but research suggests that this is not always the case. Children consistently prioritise speech tasks regardless of whether the task was assigned as primary or not (Choi, Lotto, Lewis, Hoover, & Stelmachowicz, 2008). Therefore, alternative objective behavioural measures that do not rely on as many assumptions as dual-task paradigms may be of preferable use in the measurement of listening effort.

7.2. II. Single-task Measures. Cognitive-behavioural performance on single listening tasks may prove advantageous over dual-tasks, as they do not require participants to allocate effort to two different tasks, or to consciously prioritise to one over the other. Many studies utilised verbal response time in variably demanding listening tasks to indicate mental effort, on the premise that faster response latency in these tasks is achieved through effort investment (Gatehouse & Gordon, 1990). The more difficult it is to decipher the speech; the more effort is required to provide responses quickly. Research has consistently demonstrated the relationship between degraded speech and slower verbal response time (Gustafson, McCreery, Hoover, Kopun, & Stelmachowicz, 2014; Houben, Van Doorn-Bierman, & Dreschler, 2013; Mackersie, Neuman, & Levitt, 1999). In addition, a study reporting the advantage of hearing aid amplification in reducing listening effort used faster response times as evidence for eased effort (Gatehouse & Gordon, 1990). However, studies also indicate that amplification does not improve listening effort required for speech perception (Lesica, 2018; Ohlenforst, Zekveld, Jansma, et al., 2017). Moreover, the relationship between effort and performance measures are complex, such that they may not be the best indicators of mental effort investment. Numerous situational and motivational factors drive task performance for example, tasks with specific and difficult goals lead to a higher level of performance (Locke & Latham, 1990). Additionally, performance is further mediated by goal framing, feedback, attention and effort, the individuals' abilities, motivation and self-efficacy (Locke & Latham, 1990; Lunenburg, 2011). Therefore, these motivational aspects should be considered when interpreting performance measures, and measures of effort investment. The effort-performance relationship is not straightforward and therefore, measures of performance such as response time are not reliable indicators of listening effort.

7.3. Physiological Measures

A more objective measure, the outcome of which is unaffected by compensatory effort investment, is physiological reactivity. Over the recent decades, this method has become popular within the listening effort domain, resulting in the employment of a diverse range of specific measures of both neural and autonomic physiological activity. Neural measures include event-related potentials (ERPs) (Bertoli & Bodmer, 2016), electroencephalography (EEG) (O'Gorman & Lloyd, 1988), and functional magnetic resonance imaging (fMRI) (Zekveld, Heslenfeld, Johnsrude, Versfeld, & Kramer, 2014). Autonomic measures have included pupil dilation, skin conductance, and cardiac responses: pre-ejection period (PEP) and high frequency heart rate variability (HF-HRV). Most of the studies in this field aim to demonstrate that the demand of a listening task, manipulated by using various levels of speech in noise (i.e. white noise or competing talker babble), influences the physiological state of the listener, both with and without hearing impairment (see McGarrigle et al., 2014 for a review of physiological measures).

7.3. I. Neural Measures. An EEG measures the fluctuations in electronic potential in the brain using electrodes placed on the scalp. The resultant EEG signal can be analysed in two main ways, using either the analysis of neural oscillations or time-locked averaged EEG responses. The neural oscillations are categorised into different frequency bands; the alpha frequency band is often the focus in listening effort research as it is believed to reflect the demands of mental processing (Bernarding, Strauss, Hannemann, Seidler, & Corona-Strauss, 2013). It has been found to show greater suppression during tasks with degraded auditory stimuli (Obleser & Weisz, 2012) and during 'active' as opposed to 'passive' listening activities (Dimitrijevic et al., 2017); suggesting that alpha activity may reflect invested effort as a function of listening demand. ERPs on the other hand, provide information about neural activity at specific time points in relation to presentation of specific stimuli. Research finds that ERPs to task-irrelevant stimuli (usually the presentation of a novel sound) increase in amplitude in line with increasing listening demand and thus may reflect listening effort (Bertoli & Bodmer, 2014). Most frequently referenced in the listening effort research is the P300 ERP component, which researchers consider to reflect attentional processes related to the orienting response (Combs & Polich, 2006). Studies find that the amplitude of the Novelty P3 (a component of P300 specifically related to the processing of novelty) increases with listening task difficulty (Bertoli & Bodmer, 2014, 2016) and occurs more frequently in response to cochlear implants with degraded signal quality (Bönitz et al., 2018). The relationship between listening demand and P300 amplitude may provide evidence for ERP components as a measure of effort in listening. Another measure of neural activity, fMRI, provides information about changes in blood oxygenation levels. Using this method Wild et al. (2012) demonstrated increased activity in the left inferior frontal gyrus when participants attended to degraded vs. clear speech, a possible indication of effortful listening. The various techniques used to measure listening effort via neural activity differ in the quality of the data provided, with EEG and ERPs providing precise temporal information and fMRI delivering more accurate spatial information (Pichora-Fuller et al., 2016). Because of this, the information provided from these measures is different and highly complex, and to disentangle listening effort from such findings would require further research.

In contrast to neural measures, other physiological indicators of listening effort rely on measuring changes in ANS activity in the periphery. Most of this research relies on the conceptualisation that effortful listening requires increased cognitive resources to cope with listening demand, and that the listener experiences this as increased physiological arousal. Increases in ANS activity that occur as a function of the balance between sympathetic and parasympathetic influence on the ANS can quantify physiological changes during listening.

7.3. II. Pupillometry. Probably the most popular measure of autonomic reactivity in the listening effort literature to date is pupillometry. Both branches of the ANS mediate changes in pupil diameter, because the SNS and PNS both innervate the pupillary muscles. In doing so, the two branches exert opposing constricting and dilating force on the pupil and can be under reciprocal control (Berntson et al., 1991). Changes in pupil size through ANS influence are suggested to reflect fluctuations in neural activity in the brainstem's locus coeruleus, which is involved in attention, alertness and arousal during task performance (McGarrigle et al., 2017a). The phasic and tonic modes of LC-NE system activity are characterised by differences in the release of noradrenaline (the main neurotransmitter of the sympathetic nervous system; which in part innervates the pupil) (Aston-Jones & Cohen, 2005).

The pupillary changes are reliable in indicating variations in effort and cognitive load during mental tasks (Beatty, 1982; Beatty & Kahneman, 1966); pupil dilation occurs with increased SNS activation and or PNS withdrawal, whereas constriction is mediated by PNS activation (Kruglanski et al., 2012; Wang et al., 2016). Studies in the listening effort field demonstrate that increases in pupil dilation occur as a function of changes in listening demand (Kramer, Kapteyn, Festen, & Kuik, 1997; Kramer et al., 2013; Zekveld et al., 2010). For example, pupil dilation has been used to indicate how speech perception in the presence of competing speech (Zekveld, Heslenfeld, et al., 2014) and typical classroom noise (McGarrigle et al., 2017a) affect listening effort; both of which provide important information regarding speech processing in the real world. These studies all provide evidence for a relationship between pupil dilation and listening demand, which may suggest that listening demand results in effort induced SNS reactivity.

However, changes in pupil dilation are not only under SNS control and can be mediated by age (Zekveld et al., 2011); and also PNS contamination (Wang et al., 2016). Furthermore, a number of different pupillometric parameters have been used in the literature for example, task evoked pupil dilation, peak dilation, slope or baseline pupil size; which may relate to different cognitive processes involved in effortful listening (McGarrigle et al., 2017a). For example, peak pupil dilation has been related to the orienting response (Berntson et al., 1991) and rehearsal during tasks (Kramer et al., 1997). Additionally, pupil dilation has been found to decrease with time-on-task or during the second half of listening tasks (J. Hopstaken, 2016; McGarrigle et al., 2017b), suggested to be evidence of fatigue, but could also indicate a natural fall in dilation following an orienting response. Also, often pupillary responses are small and only attained in very difficult listening demand conditions (Kuchinsky et al., 2013), or are unrelated to reports of subjective effort (Zekveld et al., 2011).

7.3. III. Skin conductance. Electrodermal activity is the variation in the electrical conductivity of the skin. Increased conductivity occurs because of increased eccrine sweat gland activity, which causes an increase in moisture on the skin's surface. Increases in skin conductance (SC) indicate increases in physiological arousal mediated by the SNS. Some research on listening effort has shown that increasing listening task complexity (Mackersie & Cones, 2011; Seeman & Sims, 2015), or increasing speaking rate (Mackersie & Calderon-Moultrie, 2016) leads to significant systematic increases in SC level. However, often these observations were found to be uncorrelated with subjective or other physiological measures of effort (Mackersie & Cones, 2011; Seeman & Sims, 2015). Furthermore, alternative manipulations of listening task demand such as signal to noise ratio were not found to affect SC (Mackersie et al., 2015; Seeman & Sims, 2015). There is partial evidence that SC could provide a measure of effort-related sympathetic activity under certain demand conditions, but findings are inconsistent.

7.3. IV. Cardiac responses. Alternative physiological methods used to quantify listening effort include measures of cardiac activity. The high-frequency derivative of heart rate variability is associated with PNS activity, and reduced PNS activity (withdrawal) is reflective of increased physiological arousal. Mackersie and Calderon-Moultrie (2016) found that decreases in HF-HRV (reflecting PNS withdrawal) were systematically observed in response to increased speaking rate during a listening task. Yet, other research found HF-HRV to decrease only under the most difficult listening situations and only for participants with hearing loss (Mackersie et al., 2015). In the same study hearing impaired individuals had significantly lower HF-HRV compared to those with normal hearing, but only for tasks with low listening demand. The findings demonstrate some evidence for myocardial parasympathetic withdrawal in response to listening demand, but the relationship is variable.

PEP is a direct measure of the force of myocardial contraction and thus mainly mediated by SNS activity. It has been widely used in research on mental effort, which will be discussed in future sections, but thus far has only been used a single time in the research on listening effort (Richter, 2016b). Richter found that PEP reactivity increased as a function of both listening task demand and the importance of successful speech compression. Not only does this research highlight the usefulness of PEP as a potential indicator of effort investment but emphasises the importance of motivational factors when considering effort investment.

Previous studies have used combinations of SNS and PNS reactivity but often by employing measures which reflect the influence of these ANS branches at different organs such as, the measures of HF-HRV and SC in the research by Mackersie et al., 2015. Although useful for understanding the physiological correlates of effortful listening, the output of nervous system activity to the organs is uneven (Mackersie &

Calderon-Moultrie, 2016). Considering this, the current literature does not provide evidence for specific changes in autonomic balance during effortful listening. Despite a number of articles and increased popularity of using physiological measures in the assessment of listening effort over recent years, theories of effort or psychophysiological models have seldom driven the physiological research. This has resulted in the employment of an array of physiological methods to assess listening effort, which often produce confounding results and complications for interpretation. Please see Table 1 for a concise summary of the measures employed thus far, as well as their advantages and disadvantages for quantifying autonomic control. Therefore, a principle aim of this PhD was to conduct a systematic analysis of effort in listening and driven by psychophysiological theory.

Table 1.

Measurements of autonomic nervous system activity employed in research on mental effort, and listening effort. The table displays the autonomic branches that the measure is associated with, as well as the advantages and disadvantages for use of the measure in psychophysiological research.

Method	Autonomic Control	Advantages	Disadvantages
Pupillometry (including: Peak Pupil Dilation; Peak Amplitude; Task-evoked Pupil Response; Baseline Pupil Size)	PNS and SNS innervation of the pupillary muscles.	Reliably changes as a function of task load/ demand as shown by Beatty and Kahneman (1966). Ability to respond quickly to changes in experimental tasks.	Pupil dilation can be caused by either decreases in PNS activity (PNS withdrawal) or by increases in SNS activity, so separation of these influences on the pupil response is near impossible. Affected by external factors e.g. light, object

			nearness, or accommodation reflex.
Skin Conductance Level and Response.	SNS activation.	Pure indicator of sympathetic innervation of the eccrine sweat glands. Continuous physiological measurement.	Limited to measuring sympathetic activity only. Can be affected by external factors e.g. room temperature.
Cardiac Measures: High-Frequency Heart Rate Variability.	PNS mediated.	Can be used in combination with other cardiac measures to quantify balance of autonomic control during effort. Continuous physiological measurement.	Can be affected by respiratory rate, and tidal volume; which is not under parasympathetic control.
Cardiac Measures: Pre-ejection Period.	SNS activation.	Indicator of beta-adrenergic activation on cardiac contractility, which is mediated by sympathetic activation. Continuous physiological measurement. In combination with other cardiac measures,	The pre-ejection period can be influenced by cardiac loading effects (preload and afterload) which change the length of PEP independently of SNS influence.

	it can quantify balance of autonomic control.

8. Thesis Aims

The studies within this thesis aim to combine psychological theories of effort and motivation with physiological measures to provide a comprehensive and theory-driven investigation into the autonomic correlates of listening effort. The following section will contain a dissemination of the findings from five studies that were conducted within the context of this thesis. Each study addresses the predictions of MIT in relation to the autonomic correlates of listening effort. Studies focus on the influence of task demand and success importance on effort when demand is known; and the impact of success importance when demand is unclear. Listening effort is defined as autonomic nervous system reactivity, specifically PNS withdrawal and SNS activation. The aim is to provide an analysis of the autonomic correlates of listening effort guided by the predictions of MIT. The research will attempt to quantify effortful listening, and its relationship to hearing fatigue and speech comprehension. The specific hypotheses for these studies are:

1. Listening effort (operationalised as PNS withdrawal and SNS activation) should increase as a function of listening demand while successful comprehension is possible.
2. Listening effort (operationalised as PNS withdrawal and SNS activation) should increase as a function of the importance of successful comprehension (listening task reward) in listening situations with an unclear demand level.
3. Listening effort should increase as a direct function of listening demand while success is both possible and the required effort is justified. The importance of success (reward) should limit the effort-demand relationship in listening tasks.

In addition, increases in subjective fatigue and effort should increase alongside autonomic activation during listening. The first two experiments within phase one of this thesis will test hypothesis 1. The second hypothesis will be tested in experiments 3 and 4 within phase two, and the final hypothesis will be tested in experiment 5 within the third and final stage of this thesis.

III. Methodology Chapter

1. Thesis Research Questions

This research aims to use existing psychological theories on effort and physiological activation to deliver a systematic programme of research that seeks to understand the autonomic underpinnings of effortful listening, to guide future research. In addition, this research aims to provide clarity regarding the ambiguous relationship between speech perception, listening effort and hearing fatigue that has been reported in the research thus far. The selected methodologies used in the studies presented within this thesis were chosen specifically to address the research aims via the following research questions:

1. Does listening effort (operationalised as PNS withdrawal and SNS activation) follow the predictions of MIT?
   a. When the difficulty of the listening task is clear does listening effort increase as a function of listening demand while speech comprehension is possible?
   b. When the difficulty of the listening task is unclear, does listening effort increase as a function of the importance of successful comprehension (i.e. task reward)?
   c. Does the importance of successful speech comprehension (reward) limit the listening effort- listening demand relationship in listening tasks while successful comprehension is possible, and the required effort for this successful comprehension is justified?
2. What is the relationship between the autonomic reactivity that occurs during listening and the subjective feelings of effort and fatigue experienced by the listener?

a. Are changes in autonomic activation during listening related to changes in the subjective feelings of effort and fatigue experienced by the listener?
b. Are changes in autonomic activation during listening related to changes in behavioural indicators of listening task performance, which have also been considered to indicate task-related fatigue or disengagement?

2. Physiological Methods

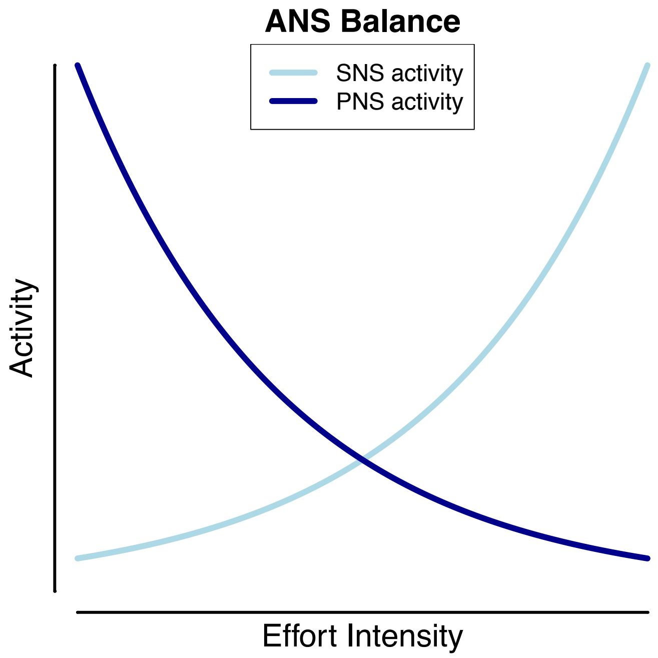

Figure 3.

A graph to illustrate the balance of autonomic control by the sympathetic and parasympathetic branches of the autonomic nervous system. The x axis indicates the intensity of effort, and the y axis indicates the activity of the ANS. At low effort intensity the PNS is highly active and exerts dominant control over the body. As effort intensity increases, the activity of the PNS reduces exponentially (PNS withdrawal) and exerts less control. Further increases in effort intensity, see further PNS withdrawal and stronger SNS activation. The SNS increases exponentially as effort intensity increases. At high effort intensity, the PNS is withdrawn and SNS is highly active, and exerts dominant control over the body.

One of the main aims of the research within this thesis was to outline a systematic theory-driven method for the researching and quantification of listening effort. The research plan and studies delivered were heavily guided by theories on the physiological underpinnings of effort, including Wright's integrative MIT hypothesis (Wright, 1996), Obrist's Active Coping Approach (Obrist, 1981), Berntson's Modes of Autonomic Control (Berntson et al., 1991) and theorisations on effort during physical activity (White & Raven, 2014), as discussed in previous chapters. A main theme that runs within these theories and models is an autonomic balance between the parasympathetic and the sympathetic nervous system, that changes as the intensity of effort increases from low to high; see figure 3 for a visual depiction of this model. The model predicts that as the intensity of effort increases, there is a subsequent change in the balance between PNS and SNS control of autonomic activity. This proposed model formed the main rationale for the physiological methods adopted for the research in this project.

2.1. Autonomic Balance

An individual's resting state is facilitated by the parasympathetic nervous system, which exerts it's influence over many organs in the human body; often termed the 'rest-and-digest' system, as opposed to 'fight-or-flight' system, which is sympathetically mediated. See figures 4 and 5 for examples of parasympathetic and sympathetic influences in the body. For example, the parasympathetic system innervates the iris sphincter muscle of the eye causing it to constrict when the PNS is active. Parasympathetic fibres originating in the Edinger-Westphal nucleus travel down the oculomotor nerve, synapse at the ciliary ganglion, then the postsynaptic fibres travel down ciliary nerves. These fibres then release acetylcholine (the neurotransmitter of the PNS) which binds to muscle receptors (M3) on the sphincter of the iris; causing the pupil to constrict (McDougal & Gamlin, 2015). Whereas, the sympathetic nervous system innervates the iris dilator muscle, causing it to dilate. The sympathetic fibres originate at the spinal cord and synapse at the sympathetic chain, the postsynaptic sympathetic fibres then travel down the long ciliary nerves. These fibres release noradrenaline (the main postsynaptic neurotransmitter of the SNS, along with adrenaline) which binds to alpha 1a adrenoreceptors on the dilator muscle, causing it to contract and resulting in pupil dilation (McDougal & Gamlin, 2015). It is important to note that, pupillary dilation can occur either by withdrawal of the PNS, which maintains homeostasis by preventing dilation through promoting constriction of the iris sphincter, or by activation of the SNS. Therefore, to use pupillometry to measure the relative contributions of the SNS and PNS branches to autonomic control of the eye is problematic.

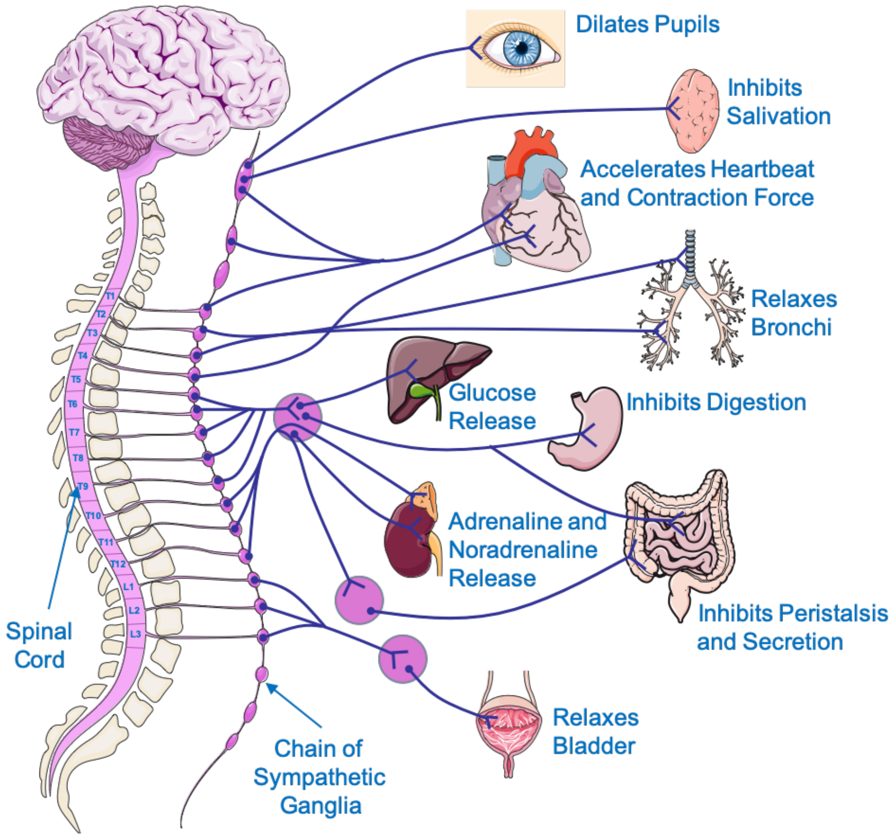

Figure 4.

The sympathetic nervous system. The system is responsible for the 'fight-or-flight' response. The figure illustrates sympathetic innervation and the various effects of this at a number of different organs throughout the body. Figure 5 was adapted from Servier Medical Art, licensed under a Creative Common Attribution 3.0 Generic License.

Previous researchers have often employed measures of autonomic reactivity that can quantify the relative contributions of the sympathetic and parasympathetic branches, such as Mackersie et al. (2015) who employed SC to measure SNS activation and HF-HRV to measure PNS activation. However, the caveat lies in that sympathetic output to the organs is not uniform; therefore, an ideal measure of autonomic balance should measure both SNS and PNS reactivity at a single organ. This problem can be resolved using specific measures of cardiac reactivity.

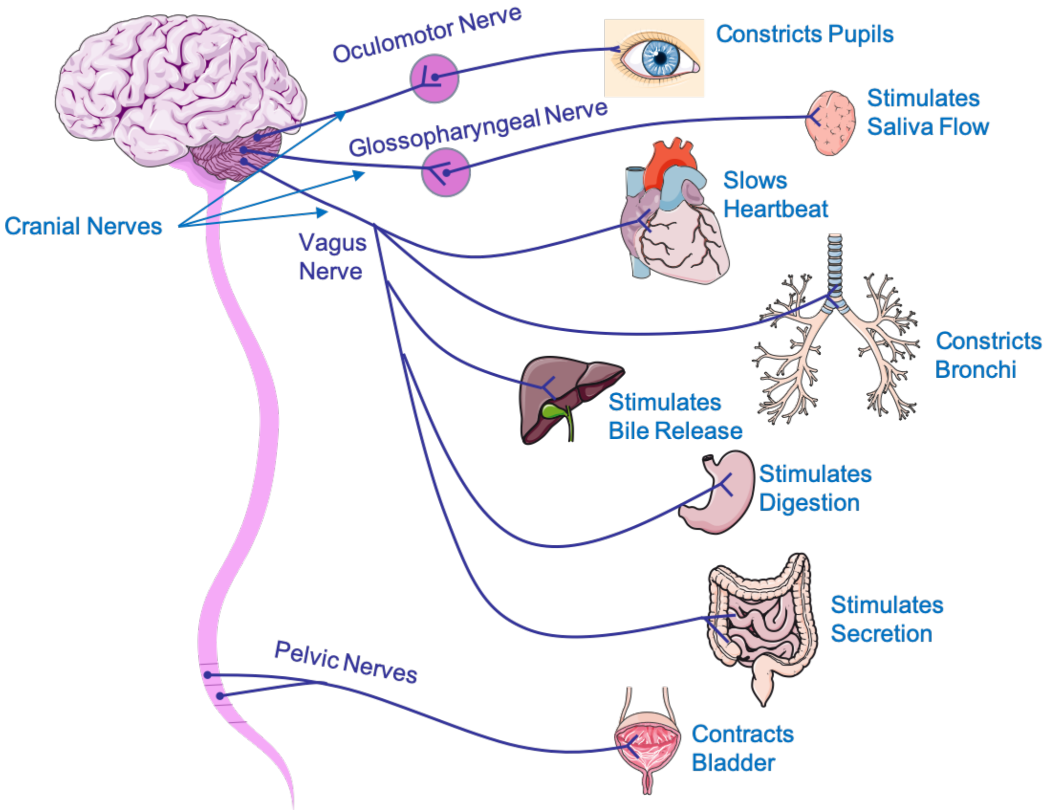

Figure 5.

The parasympathetic nervous system. The system is responsible for 'rest-and-digest' and maintaining homeostasis. The figure illustrates parasympathetic innervation and the various effects of this at a number of different organs throughout the body. Figure 4 was adapted from Servier Medical Art, licensed under a Creative Common Attribution 3.0 Generic License.

The regulation of cardiac reactivity is mediated by the PNS and the SNS, both exerting their influence to differing degrees depending on the individuals current state (for example, during effortful activity, stress, or arousal).

2.1. I. Parasympathetic and Sympathetic Cardiac Control

The heart's internal pacemaker, the sinoatrial node (SAN), generally controls heart rate. The cells in the SAN generate their own electrical activity and without any external input they maintain a heart rate of around 60-100 beats per minute. However, both branches of the autonomic nervous system, the PNS and the SNS, act upon the heart's internal pacemaker to influence cardiac activity in response to the external environment. The PNS innervates the cardiac muscle via the vagus nerve, it maintains cardiac homeostasis and decreases the heart rate. The vagus nerve releases acetylcholine which binds directly to receptors on the cardiac muscle to slow down heart rate. Alternatively, the sympathetic adrenergic nerves of the SNS release noradrenaline which binds to beta-adrenergic receptors on the cardiac muscle cells. When these receptors are activated heart rate increases, and the force of cardiac contraction is increased. The cardiac system responds more slowly than alternative measures of ANS reactivity (such as pupil responses or electrodermal activity), cardiac responses to external environmental changes mediated by the PNS occur within 1 second, whereas changes mediated by the SNS occur after 5 seconds (Nunan, Sandercock, & Brodie, 2010).Furthermore, at least 5-minutes of continuous data is required for accurate measurement of heart rate variability in the frequency domain (Bourdillon, Schmitt, Yazdani, Vesin, & Millet, 2017).

Due to the impact of very low and high body mass on blood pressure and cardiac functioning (Martins, Tareen, Pan, & Norris, 2003; Sheema & Malipatil, 2015; Subramaniam, 2011); the weight and height of participants was measured for the calculation of BMI. It was ensured that no participants displayed a BMI <18.5 or >30; as these values may affect the cardiac functioning of individuals independently of sympathetic or parasympathetic influence.

All physiological measures were collected during baseline and task periods in all experiments within this thesis, task and baseline periods were indicated by markers manually entered into the data collection software at the beginning and end of each task and baseline condition. All task conditions within the experiments lasted for approximately 6 minutes. The first 5 minutes of the cardiovascular data was used for data analysis in the task period; as this this the data which is most sensitive to task characteristics, and has been less influenced by learning effects which may have occurred towards the end of the experimental condition. The last 5 minutes of the baseline cardiovascular data was used for data analysis; this is the part of the baseline which most likely represents true rest, as the cardiovascular system has had the most time to return to resting state following the previous task condition.

2.2. Respiratory Sinus Arrhythmia (RSA)

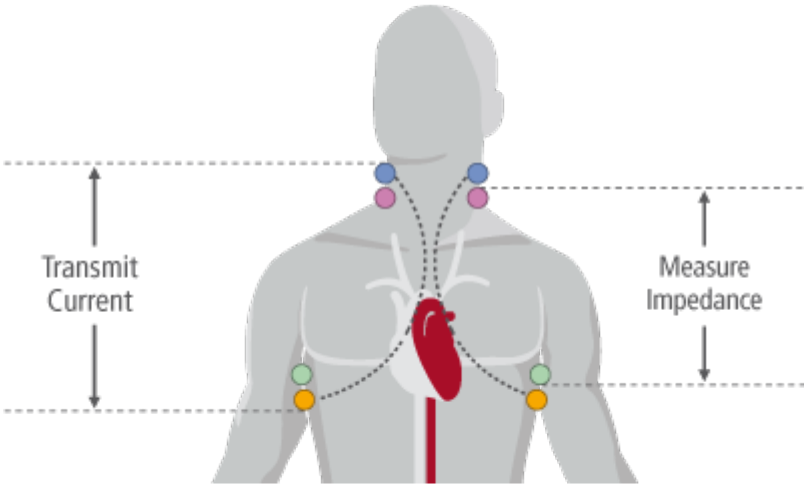

Figure 6.

A figure illustrating the electrode configuration employed by the CardioScreen 1000 for the measurement of an ECG and an ICG. Two pairs of electrodes are placed on either side of the neck along the axillary lines, and two pairs are placed on either side of the thorax at the height of the xiphoid. The outer electrode of each pair (orange and blue) emit a small electrical current, and the inner electrodes (pink and green) are used for measurement.

A CardioScreen 1000 (Medis Medizinische Messtechnik GmbH, Illmenau, Germany) was employed in the studies within this thesis to measure electrocardiography (ECG) and impedance cardiography (ICG). The CardioScreen sampled both an ECG and ICG at a rate of 1000Hz. Four pairs of electrodes are placed on the skin in the configuration shown in figure 6. The outer electrodes in each pair pass a very low constant, alternating current (1.5 mA, 86 kHz) through the thorax. The inner electrodes in each pair measure the voltage caused by the current.

The ECG sampled by the CardioScreen records the electrical activity in the heart, recorded in a continuous signal that displays the phase of the electrical signal as it travels through the heart during each heartbeat. Please see figure 7 for a labelled diagram of an ECG trace. The electrical activity starts at the SAN, the heart's pacemaker, in the right atrium of the heart. The activity travels to the right and left atria causing them to contract and force blood into the ventricles (the P wave on the ECG trace). The electrical signal travels from the atria to the ventricles via the atrioventricular node which slows down the electrical signal allowing the ventricles fill with blood. The electrical signal then travels down the bundle of His pathway and Purkinje fibres to the ventricles. The electrical signal causes the ventricles to contract from left to right, and pump blood into the lungs and body (represented by the QRS waves); the Q wave therefore indicates early depolarisation of the left ventricle. Following this, the ventricles recover to their normal electrical state (T wave).

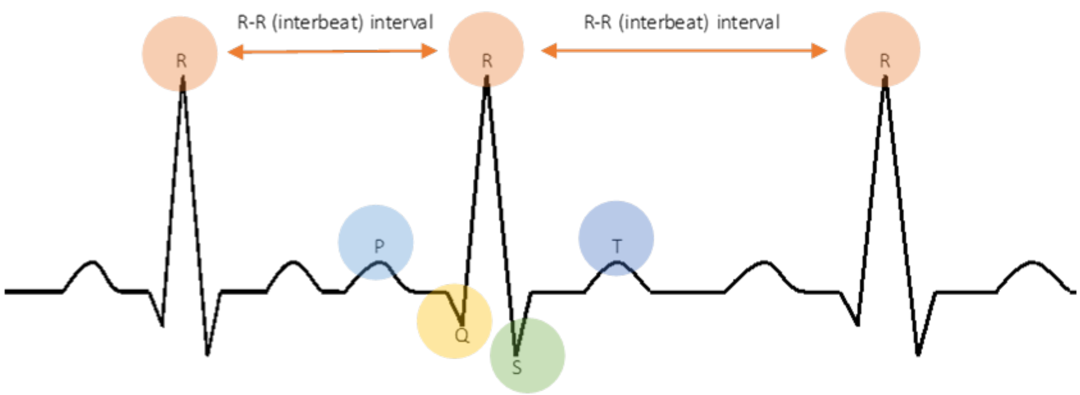

Figure 7

A labelled diagram of an ECG trace, indicating the P-point, the QRS complex, and the T-point. The figure also illustrates heart rate variability, by labelling the variable difference between the R-R (interbeat) intervals.

The time between each heartbeat (or the inter-beat interval, IBI) is derived from the interval between each R wave (or peak) on an ECG trace. The R-R interval is used to measure heart rate, as well as the variability in the time difference between each heartbeat. Heart rate variability indicates the variability between each IBI. Heart rate variability analysed in the frequency domain, demonstrates how the variability is distributed within frequency bands. The high-frequency component reflects variability in heart rate related to respiratory frequency; which is mediated by parasympathetic vagal control (Berntson et al., 1997; Grossman, 2004; Grossman & Taylor, 2007).

2.2. I. RSA Data Processing

The IBI series was exported from the CardioScreen software, and subsequently loaded into specialist analysis software; BlueBox (Richter, 2009). The R-peaks of the ECG signal were detected offline in BlueBox (Richter, 2009); this included the manual detection of peaks, removal of falsely identified peaks and ectopic heart beats. The resulting interbeat interval series was then loaded into Kubios analysis software (version 2.0, Biomedical Signal and Medical Imaging Analysis Group, University of Kuopio, Finland); using the Fast Fourier Transformation (FFT) technique, the high-frequency band (0.15 – 0.40 Hz) of heart rate variability (HF-HRV); which reflects RSA was calculated (Malik et al., 1996; Tarvainen, Niskanen, Lipponen, Ranta-aho, & Karjalainen, 2014). The FFT is a mathematical algorithm which uses power spectral density (PSD) analysis to calculate how power (or variability) is distributed as a function of frequency. The FFT categorises each frequency component, including the high-frequency; which is of interest in this research program due to its relationship to parasympathetic activity on the myocardium. These frequency components are then expressed in normalised units (n.u.); which represents the relative contribution of each component to the total variance (Huston & Tracey, 2011). Pharmacological studies show that administering acetylcholine antagonists results in a decrease in the high-frequency power component, while it is increased by vagus nerve stimulation (Malik et al., 1996). Highlighting the fact that the high frequency component reflects parasympathetically mediated vagal control of cardiac activity.

However, RSA is influenced by respiration rate, which is not under parasympathetic control, the first four studies in this thesis failed to control for this variable and thus the measure of RSA is not a completely accurate measure of PNS reactivity (Grossman, 2004). In Experiment 5, respiratory frequency was measured to control for its possible influence on RSA using two BioPac SS5LB respiratory effort transducers worn over the participant's clothes, one at the chest and the other around the abdomen (BIOPAC Systems Inc., Goleta, CA, USA). The elasticised belts measured the change in thoracic and abdominal circumference using a BIOPAC MP30 system, sampling the signal at 50Hz. The respiratory data was analysed in BioPac Student Lab 4.0 (BIOPAC Systems Inc., Goleta, CA, USA). The software calculated the mean, maximum, minimum and standard deviation of respiration rate (in Hz) from the combined respiratory waveform (arithmetic mean of thoracic and abdominal respiration) for all periods. Any participants with a mean respiratory frequency outside the 0.15-0.40 Hz (high frequency) band were removed from statistical analyses.

2.3. Pre-ejection Period (PEP)

As well as recorded an ECG, the CardioScreen 1000 also measures impedance cardiography (ICG). Each of the four pairs of the electrodes contain an inner (measurement electrode) and outer (current electrode); the outer electrodes in each pair pass a very low constant, alternating current (1.5 mA, 86 kHz) through the thorax. The inner electrodes in each pair measure the voltage caused by the current. This voltage corresponds with impedance changes caused by variations of the blood volume in the thoracic part of the aorta and the alignment of the orientation of red blood cells when the blood is pumped out of the left ventricle of the heart into the aorta. The measurement of voltage results in an impedance pulse wave (IMP), the derivative of which is the ICG waveform (see figure 8 for a labelled ICG trace). Within the ICG trace, one can locate certain points in the cardiac cycle based on the blood volume level. The B point corresponds to the opening of the aortic valve; the C point corresponds to the maximum level of impendence; and the X point corresponds to the closing of the aortic value.

Combining the measure with ECG provides meaningful information about specific cardiac events. The pre-ejection period (PEP) is the time between the electrical depolarization of the left ventricle (Q point on an ECG trace) and the opening of the aortic value (or the start of blood ejection into the aorta). The length PEP is directly dependant on the force of myocardial contraction. This parameter is dependent on sympathetically mediated beta-adrenergic activity on the cardiac muscle. The length shortens after beta-adrenergic stimulation due to increased force of contraction meaning the blood is pumped more quickly and forcefully from the ventricles into the aorta. Research has shown that beta-adrenergic receptor agonists (such as adrenaline) lead to significant decreases in PEP (Mezzacappa et al., 1999); and beta-adrenergic blockades using antagonists (beta-blockers) prevents decreases in PEP from occurring (Cacioppo et al., 1994).

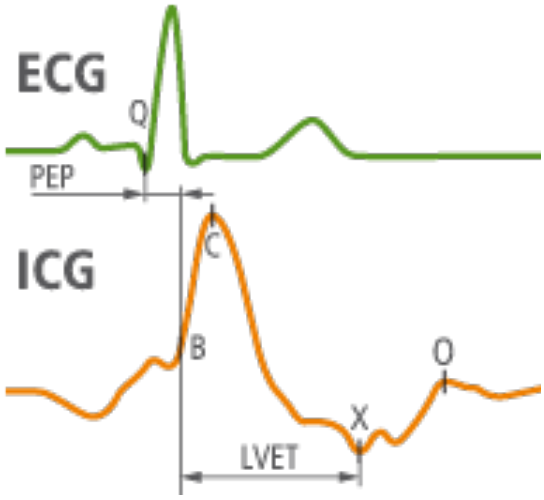

Figure 8.

A figure showing an ECG, with the Q-point, indicating left-ventricular excitation marked. As well as a labelled ICG trace. The time interval between the ECG Q-point and the ICG B-point, which indicates the opening of the aortic value, is the pre-ejection period (PEP).

2.3. I. PEP Data Processing

Myocardial sympathetic activity was quantified as PEP using the ICG and ECG signals collected from the Cardioscreen 1000 impedance cardiograph (Sherwood et al., 1990), the signals were then analysed offline in BlueBox analysis software (Richter, 2009). The interbeat interval (IBI) series for the baseline and task periods collected from the ECG were loaded into BlueBox where a peak finder located all R-peaks. The researchers manually identified and corrected any missed, falsely identified peaks or ectopic beats, to produce an IBI series for the baseline and task periods. BlueBox averaged the dZ/dt signal derived from the ICG along with the ECG signal over periods of 60 seconds to create ensemble averages. PEP (in milliseconds) was then calculated for each average using manual scoring. The researcher computed PEP as the interval between the onset of left ventricular depolarisation, indicated by the Q-point on the ECG, and the left ventricular ejection into the aortic valve, indexed by the B-point on the ICG; both of which were manually checked and identified.

The PEP can also be influenced by the level of cardiac preload or afterload. Increased preload, or amount of blood that enters the ventricles when the heart muscle is relaxed, stretches the myocardial fibres and therefore increases the force of myocardial contraction (via the Frank Starling mechanism). This shortens the length of PEP without any sympathetic beta-adrenergic influence (Newlin & Levenson, 1979). Heart rate provides an indicator of cardiac preload; as slower heart rate allows for a longer ventricular filling time and thus increased preload. Increased afterload, or aortic diastolic pressure, is the load against which the left ventricle contracts. The pressure in the left ventricle must exceed the pressure in the aorta for the aortic valve to open. If afterload increases, indicated by increased diastolic blood pressure (Obrist, Light, James, & Strogatz, 1987; Sherwood et al., 1990), the length of PEP increases because it takes longer for ventricular pressure to rise above the aortic pressure. Considering this, decreased PEP can only reflect increased sympathetic beta-adrenergic influence when accompanied by stable or increased heart rate and diastolic blood pressure (Richter, Friedrich, & Gendolla, 2008). In all studies within this thesis, changes in diastolic blood pressure and heart rate were used to verify that any observed changes in PEP resulted from increased sympathetic influence and not due to changes in cardiac preload or afterload (Sherwood et al., 1990).

3. Subjective Measures

Subjective measures were employed in this research to answer specific research questions about the relationship between the autonomic reactivity that occurs during listening and the subjective feelings of effort and fatigue experienced by the listener. The main aim is to provide information that might help clinicians to understand the emergence of feelings of effort and fatigue experienced by hearing impaired individuals, and whether it is related to physiological exertion.

3.1. NASA Task Load Index (NASA-TLX)

Subjective effort was measured in all studies using a modified version of the NASA Task Load Index (NASA-TLX) (Hart & Staveland, 1988). The version contained two relevant subscales (mental demand and effort) from the original NASA-TLX. The participant responded using a five-point Likert scale, where one represented "very low" and five was “very high". The sum of responses from these two questions quantified total ‘effort’, thus subjective effort could range from two (lowest effort) to 10 (highest effort).

3.2. Six-Item Fatigue Questionnaire

In experiment 1, subjective fatigue was quantified using a novel six-item fatigue questionnaire which addressed present feelings of fatigue using questions such as, “At this time, do you feel well rested?” and “How worn out are you currently?”. Three of which were framed positively and three negatively. The participant responded via a five-point Likert Scale where one represented "much less than usual" and five represented "much more than usual". See Appendix 2 for the questionnaire items. Items were scored from 1-5, and reverse scored for negatively framed items. The total score then quantified the participants current state of subjective fatigue. The higher the score on the fatigue questionnaire indicated increased subjective fatigue. Baseline and task fatigue scores could range from six (lowest fatigue) to 30 (highest fatigue). Change scores between task and baseline scores on the fatigue questionnaire indicated changes in subjective fatigue.

3.3. Nine-Item Fatigue Questionnaire

For use in Experiments 2-5, a novel 9-item fatigue questionnaire (see appendix 3 for the questionnaire items) was used to measure subjective fatigue, the questionnaire was administered before and after each task period. For each item two comparative adjectives were presented on the screen, and the participant selected the word which best described their current state. Three words for fatigue (fatigued, tired, worn out) and three words for alertness (energised, lively, well rested) were displayed in all possible combinations to create nine items. The data was analysed by giving a score of '1' each time the participant clicked on a word that represented 'fatigue', whereas words that represented 'alertness' were scored as '0'. Therefore, fatigue questionnaire ratings could range from 0-9, and the change between task and baseline scores indicated task-related changes in subjective fatigue

4. Behavioural Tasks

All behavioural listening tasks were presented to participants on a designated experimental computer using computerised experiment generation software (Inquisit Version 5 by Millisecond Software, Seattle, WA). Inquisit controlled the presentation of all behavioural tasks and collected the participant's responses, including percentage of correct responses and response latency. The volume level of the experimental computer was set to a fixed, permanent level. The sound level was checked prior to each experiment to ensure that the volume produced was suitable for the experimental stimuli. These checks were performed using a TENMA™ 72-860 Sound Level Meter (TENMA™ by Premier Farnell UK Limited, Leeds, UK) that allowed for the measurement of dB SPL through headphones that would be worn by the participant during the experiment. All audio stimuli in the experiments was presented to participants through overhead headphones. Lightweight SONY overhead headphones (version MDR-ZX310) with padded earcups were used for this purpose, to ensure maximum comfort for participants.

4.1. Pure Tone Audiometry

All participants prior to each experimental testing session completed a modified Pure-Tone Audiometry Assessment. The purpose of this pre-screening session was to ensure that all participants who took part had no hearing loss, and similar hearing thresholds. In this modified version of Pure-Tone Audiometry; participants wore headphones to listen to seven pure tones at 20dB and frequencies of 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 6000 Hz for 1 second each. After each tone, the participant indicated if they heard it or if they wished to repeat it by clicking an option on the computer screen ('yes', 'no' or 'repeat'). The researchers invited participants who identified a minimum of five tones to continue their participation and thanked those who did not for their time.

The 0 dB reference values were determined in a calibration procedure by four individuals with good hearing (0 dB threshold for all frequencies in a standard pure-tone audiometry (British Society of Audiology, 2011). In the calibration procedure four individuals with no diagnosed hearing impairments were presented with each pure tone and asked whether the tone was perceptible. The dB SPL level of the tone was reduced in Inquisit software by -1dB in each trial until the individual indicated that the tone was no longer perceptible. This constituted the individual's 0dB reference value. The researcher calculated the mean sound level of each individual's 0dB reference values for each tone. This resulted in 0dB reference values for each of the 7 pure tones. The sound level was then attenuated by 20dB SPL within the Inquisit software, and subsequently measured by the Sound Meter to confirm the sound level.

4.2. Word Recognition Task (WRT)

The Word Recognition Task (WRT) was created for use in the initial experiment conducted within this program of research (Experiment 1); the aim was to create an objective listening task with 3 levels of listening demand to be used in a between subject's experimental design. During the task, the participant was required to listen to audio stimuli (a single target-word, or a single target word in unison with a single competing word, or a single word in unison with two competing words). The participant was then required to identify the target word from four options on a computer screen (one of which was the target word, and the other three were distractor words; which were not used as the competing words).

The WRT had three versions: a low demand version (single target word); a moderate demand version (target and single competing word); and a high demand version (target and two competing words). A list of 1-40 common English words between three and nine characters in length was created to be used for the audio stimuli. The words in included common foods, animals and colours such as, apple, orange, green, carrot, cat, and ginger. The words were assigned a number from 1-40 and combined using a staggering method to create the three versions of the task; please see table 2. for a visual description of this method.

Table 2.

The use of the 40-item word pool to create three demand versions of the WRT. T indicates the Target word and C indicated the Competing words.

Low Demand WRT	Moderate Demand WRT	High Demand WRT
Word 1 (T)	Word 1 (T) + Word 40 (C)	Word 1 (T) + Word 40 (C) + Word 39 (C)
Word 2 (T)	Word 2 (T) + Word 1 (C)	Word 2 (T) + Word 1 (C) + Word 40 (C)
Word 3 (T)	Word 3 (T) + Word 2 (C)	Word 3 (T) + Word 2 (C) + Word 1 (C)
Word 4 (T)	Word 4 (T) + Word 3 (C)	Word 4 (T) + Word 3 (C) + Word 2 (C)
Word 5 (T)	Word 5 (T) + Word 4 (C)	Word 5 (T) + Word 4 (C) + Word 3 (C)

…	…	…
Word 40 (T)	Word 40 (T) + Word 39 (C)	Word 40 (T) + Word 39 (C) + Word 38 (C)

All the words were created using Ivona Text-to-Speech Software, which turns text into lifelike speech (IVONA Software, Gdynia, Poland). The voice used to articulate the words was a British English female voice. The audio files containing the words were subsequently loaded into digital audio editing software, Audacity (Version 2.2.2, Pittsburgh, Pennsylvania, US). Audacity was used to combine the audio files to create the stimuli for the moderate demand WRT (target word with a competing word) and the high demand WRT (target word with two competing words).

All three versions of the WRT consisted of 10 practice trials, and 30 task trials separated by a 10-minute baseline period. Experiment generation software, Inquisit, controlled the presentation of the experimental stimuli and collected the participants responses, including the number of correct responses and response latency. Within each trial participants wore headphones to listen to a target word, participants were informed that the target may be a single word, or a word embedded in other speech. After they heard the audio stimuli participants were asked what they thought the target word might be. Participants were required to identify the target from four options on the computer screen, none of these options were the distractor words used in the audio stimuli. Four response options were included to reduce the likelihood of guessing, thus providing more informative data. After each trial, a feedback message (‘correct answer’ or ‘incorrect answer’) appeared on the screen. After the practice trials, the participant received a score out of ten.

The stimuli used in this task may pose disadvantages due to the large variation in word length, which means some target words (if longer) may have been easier to identify in the competing babble than shorter words. Similarly, shorter target words may have been harder to identify when the competing words were longer. However, this may also be a more ecologically valid task as it likely reflects speech perception in daily life. Furthermore, in order to maintain the life-like authenticity of the text-to-speech voices, the words were not synthetically altered to standardise the length.

4.2.I. Data Analysis of Behavioural Tasks

The Inquisit data file, which contained information about the number of correct responses in the 30-trial WRT, and the response latency was loaded into RStudio statistical computing software (RStudio, Inc., Boston, MA). In RStudio, the mean number of correct responses was calculated for each WRT task condition, as well as the mean response latency. Number of correct responses was used to quantify task performance. Whereas response latency was used to quantify objective fatigue. It is hypothesised, in line with previous research, that slower responses may indicate a withdrawal or disengagement of effort from the task. This disengagement may be consistent with a short-term, task-related fatigue based on the idea that an individual evaluates the effort or resources required for a task. If the task outcomes are not 'worth' this investment, or the resources are not sufficient; fatigue arises to encourage an individual to re-evaluate their resource investment, withdraw effort and conserve resources (Hockey, 2011). It should be noted that all behavioural listening tasks employed in the research within this thesis, to be discussed in the following sections, were analysed in this way: number of correct responses (task performance) and response latency (objective fatigue). The inclusion of these measures provides valuable information about how the investment of listening effort, and the associated physiological reactivity translates into speech comprehension, and withdrawal from trying to understand speech due to task-related fatigue.

Clearly, there are also caveats to the inclusion of these measures. Most importantly, how they translate to understanding speech perception, listening effort, withdrawal from social interactions, and fatigue experiences of individuals in the 'real-world' with hearing impairment. It is possible, that behaviours in the laboratory setting, do not translate to the experiences of hearing-impaired people in daily life. The laboratory is temporary, but hearing impairment is permanent and difficulties with speech perception are unavoidable for these individuals. Listening effort investment may not only reflect ability, but also the individuals' willingness and understanding of the consequences of investing effort; fatigue. For hearing-impaired persons these consequences are far greater, the cost of disengagement could mean further social isolation and reduced well-being, which may encourage the continual investment of resources.

Task performance also reflects individual characteristics independent from effort investment such as, ability, and self-efficacy (Locke & Latham, 1990; Lunenburg, 2011). Additionally, often response latency of incorrect responses is not a reliable measure, as research reports that incorrect responses are consistently related to longer response times (Wilding, 1971). However, due to the inclusion of 'impossible' conditions in some of the behavioural tasks in research in this thesis, where responses may be exclusively incorrect, it is necessary to also include incorrect responses in latency analysis to provide a holistic picture of task performance and disengagement (related to task fatigue).

4.3. Speech in White Noise Tasks

Speech in White Noise Tasks were employed in experiments 2-5 within this thesis. This new behavioural task paradigm was employed after Experiment 1, as the stimuli in the first experiment possessed several caveats. A task which includes longer stimuli would be favourable for both ecological validity and for use in conjunction with slow responding cardiovascular measures. As stated earlier, the SNS takes at least 5 second to respond to internal and external stimuli. Therefore, a task comprising short-lasting stimuli (<1 second words) with 'rest' periods in between, wherein participants provide responses and wait for the next stimulus presentation is not ideal for use with cardiac measures. Nor would it be representative of daily life listening situations. The speech stimuli used in the Speech in White Noise tasks were novel stories created by the researcher for the purpose of these experiments, a novel task was created as there are limited standardised listening tasks available which provide long enough stimuli presentation periods.

All stories were created using Ivona Text-to-Speech Software (IVONA Software, Gdynia, Poland). Care was taken to ensure all stories possessed similar semantic structure, please see Appendix 4 for examples of the stories used within the speech in noise tasks. However, due to the number of trials required in each speech in noise task condition, the content of the stories was altered in each trial. This reduced the likelihood of learning effects in the within-subject designs. Yet, it may have impacted on trial-by-trial difficultly. The length of the stories ranged from 23-30 seconds long. The stories were always presented at 50dB in all trials, in all speech in noise tasks described in the following sections. The 50dB SPL level was ensured by using the Sound Meter to confirm the sound output level of the experimental computer until it consistently measured 50dB SPL on average during the presentation of the speech. A level of 50dB SPL is consistent with quiet conversation (Plack, 2013); this level was employed for a number of reasons. The first being ethical, this level is soft so ensures that individuals with normal hearing will remain comfortable during the experiments. It also ensures that the level is low enough for white noise to mask the speech completely in the 'impossible' listening conditions employed in this research, without the white noise reaching dangerously loud levels. Furthermore, quieter stimuli ensure that the tasks are not too easy, and still engaging for individuals with normal hearing. The dB SPL level of the speech stimuli would likely need to be adapted if this task paradigm were to be used with hearing impaired persons.

The speech files were subsequently loaded into digital audio editing software, Audacity (Version 2.2.2, Pittsburgh, Pennsylvania, US). Audacity was then used to generate, and embed the speech in, white noise; which was used to create different speech in noise stimuli for experiments 2-5. The white noise generated always lasted for 32 seconds to ensure all trials and speech in noise conditions remained of comparable length. The speech was presented after the first two seconds of white noise. A single file consisting of speech embedded in white noise was then exported from Audacity to be presented in the speech in noise tasks via Inquisit experiment generation software.

4.3. I. Speech in Pure White Noise Task (SiWN)

The Speech in Pure White Noise Task (SiWN) is a novel listening task, created for use in Experiment 2 of this thesis. The SiWN has four listening demand conditions; low, moderate, high and impossible. Each condition consists of two practice trials and ten task trials. A pool of 48 Ivona text-to-speech short stories were randomly assigned to each of the four conditions. Using Audacity audio editing software, the stories were embedded in white noise. The dB level of the white noise for each condition was determined in a piloting procedure, as described below.

4.3. I. a. Speech in Pure White Noise Task Piloting

The audio stimuli used for Experiment 2 was determined through piloting. Six participants with normal hearing participated in an initial pilot study; each participant completed a listening task paradigm in which they completed pairs of trials of increasing listening demand. In each trial, the participant listened via headphones to a 32-second short story spoken by an English female voice, in the presence of white noise, and answered a single comprehension question. The short story audio clips were created using an online text-to-speech generator (IVONA Software, Gdynia, Poland). The audio files were subsequently loaded into digital audio editing software, Audacity (Version 2.2.2, Pittsburgh, Pennsylvania, US), which was used to embed the speech in white noise. The level of white noise was adjusted in Audacity by increasing or decreasing the volume by 3dB, to create a listening task paradigm of increasingly difficult trial pairs. After each pair of trials, the participant was asked to rate the difficulty of the trials (low, moderate, high or impossible). In the first pair of trials, the level of white noise was decreased by 15dB in Audacity, translating to a speech signal to white noise ratio (SNR) of 0dB. The stimuli for subsequent trial pairs was created by increasing the -15dB white noise level by increments of 3dB, resulting in trial pairs with SNRs of -2dB, -3dB, -5dB and -6dB. The difficulty level increased until the point at which participants rated the task to be 'difficult', at this point participants completed the same two trial pairs they rated to be difficult and two pairs at the next difficulty level. The participant was asked to rate the difficulty of the last two trials. The experiment ended once participants had rated the trials the last two trials to be impossible. The pilot study showed that the SNR levels from -2dB to -5dB were rated to be difficult by half the participants.

However only two trials were used in this pilot, which would not be reflective of the planned listening task to be used in the experiment. Therefore, a second pilot study was used containing 16 trials at -3dB SNR (this means that the volume of the white noise was decreased by 9dB in Audacity). Participants were asked a single comprehension question following the trial. Seven participants with normal hearing participated; six of which rated the task as 'difficult' and one participant rated it as 'impossible'. The mean performance score was 11 out of 16.

Based on these findings, the -3dB SNR stimuli was used to represent the difficult listening task conditions (white noise at -9dB in Audacity). In order to have a larger difference in difficulty level the 0dB SNR stimuli was used in the moderate listening condition (white noise at -15dB in Audacity), as the difficulty level above this was rated as difficult in half the pilot participants. In order to ensure the low demand listening task was highly easy, stimuli with a much higher SNR than used in the pilot studies, 10 SNR (white noise at -36dB in Audacity) were employed. Similarly, to ensure that the impossible condition was truly impossible, stimuli at a lower SNR than employed in the pilot study, -9dB SNR (white noise was presented at +3dB higher than the speech in Audacity) were used.

Inquisit presented the four conditions in a random order to each participant, and each condition contained two practice and ten task trials. In each trial, the participant wore the Sony experiment headphones to listen to a 32-second short story spoken by a female voice, embedded in white noise. The speech was presented at 50dB. The white noise in the low demand condition was presented at -36dB lower than the speech, at -15dB in the moderate condition, at -9dB in high demand condition, and at +3dB higher than the speech in the impossible demand condition. After hearing the audio, the participant had 5 seconds to respond to a multiple-choice comprehension question. Participants were informed that there was a 5-second response window and encouraged to respond as quickly and accurately as possible. In each condition the participant completed two practice trials, after which they received feedback (‘correct answer’ or ‘incorrect answer’), and 10 task trials. Task performance could therefore range from 0 - 10. The participant was informed that seven or more correct responses would earn them a £5 Amazon Voucher.

4.3. I. b. Speech in Pure White Noise Task with an Unclear Demand (SiWN-U)

This version of the SiWN was employed in Experiment 3 of this thesis; it is a speech in noise task wherein the participant does not know the required performance standard for task success (unclear demand). The task comprises four reward conditions: no reward, low reward, moderate reward, high reward. The rewards were provided upon successful completion of the task: £0 in the no reward condition, £2 in the low reward, £4 in the moderate condition, and £6 in the high reward condition. In each reward condition there were 10 task trials. A pool of 40 Ivona text-to-speech short stories at 50dB SPL, ranging in length from 23-30 seconds, were randomly assigned to each of the four conditions, with 10 stories in each. The speech audio was loaded into Audacity audio editing software, wherein the speech was embedded in white noise. After hearing the audio stimuli, participants were given a 5-second response window to answer a multiple-choice comprehension question about an aspect of the audio stimuli. There were three choices, in order to reduce the likelihood of guessing and increase the likelihood of meaningful response data.

In order to create a task in which the conditions have an unclear demand level two task characteristics were manipulated: 1) trial-to-trial difficulty; 2) unknown target score. So that participants were not able to predict the difficulty of the upcoming trial, the trials within each condition were of differing difficulty. The white noise presented with the trials in each condition remained fixed but varied from very quiet (-36dB quieter than the speech) to loud (-0dB; at the same level of the speech). The white noise was generated, manipulated, and combined with the speech in Audacity software. Table 3 demonstrates the levels of white noise used in each trial within the four SiWN-U conditions.

Table 3.

The level of white noise employed in each of the 10 task trials in all four conditions of the SiWN-U Task. The order of the trials was randomised by Inquisit experiment generation software in each condition. The difficulty level, though unclear to the participant, remained fixed and the same for each condition; meaning that the same amount of easy and difficult trials were presented in each condition of the SiWN-U.

-36dB	-30dB	-24dB	-18dB	-15dB	-15dB	-9dB	-9dB	-3dB	-0dB

The second task characteristic manipulated to ensure task demand remained unclear was the lack of clarity regarding the target score participants needed to attain to earn the reward. All participants were primed to respond as quickly and as accurately as possible. At the beginning of each reward condition, the participant was informed that they would complete 10 task trails, and that the computer would select a target score ranging from 5 to 10 correct responses. Participants were made aware that correctly answering enough of the multiple-choice questions to achieve this target score, would earn them the reward offered for that condition. The reward value was announced before the condition: either a £0 Amazon Voucher, a £2 Amazon Voucher, a £4 Amazon Voucher or a £6 Amazon Voucher. In this task, the difficulty level remained constant in all four conditions, but it remained unclear to the participant due to the varying level of white noise and the ambiguity of the target score.

4.3. I. c. Speech in Pure White Noise Task with an Easy Demand Level (SiWN-Easy)

Table 4.

The level of white noise employed in each of the 10 task trials in all four conditions of the SiWN-Easy Task. The order of the trials was randomised by Inquisit experiment generation software in each condition.

-18dB	-18dB	-24dB	-24dB	-24dB	-30dB	-30dB	-30dB	-36dB	-36dB

This version of the SiWN was employed in Experiment 4 of this thesis; it is a speech in noise task with a low listening demand level. The task consists of four conditions, over within participant and between participant factors. The between groups factor is task demand clarity (clear vs. unclear). The within groups factor is reward (low: £1 vs. high: £9).

The task consists of 10 speech in noise trials. A pool of 20 Ivona text-to-speech short stories at 50dB SPL, ranging in length from 23-30 seconds, were randomly assigned to each of the two reward conditions, with 10 stories in each. The speech audio was loaded into Audacity audio editing software, wherein the speech was embedded in white noise. After hearing the audio stimuli, participants were given a response window to answer a multiple-choice comprehension question about an aspect of the audio stimuli. There were three choices, in order to reduce the likelihood of guessing and increase the likelihood of meaningful response data.

In order to create a task with a low listening demand level the speech was combined with low dB levels of white noise; the level of white noise presented in each of the 10 trials is provided in table 4. The white noise was generated, manipulated, and combined with the speech in Audacity software. In all trials the speech could be heard clearly over the top of the white noise, but only one participant group was made aware of this fact (the clear demand group). In the other group, the aim was to present the task as having an unclear performance standard. In order to achieve this the clear and unclear tasks differed with respect two three characteristics: 1) Verbal and on-screen task instructions; 2) Response window; and 3) Criterion to achieve a reward. Please see table 5 for a list of these task-related manipulations.

Table 5

A table displaying the task-related manipulations in the between-groups conditions (clear vs. unclear). The instructions provided to participants with respect to each task characteristic (task instructions, response window, and reward criteria) are provided.

SWiN-Easy Condition	Verbal / on-screen instructions	Response window	Criterion to achieve task reward
Clear (£1) Clear (£9)	Speech will be presented in low white noise. The noise will be quiet enough to hear the speech clearly at all times.	You have 5 seconds to answer.	You must answer nine comprehension questions correctly (out of 10) to earn a reward voucher.
Unclear (£1) Unclear (£9)	Speech will be presented in white noise that will range from very quiet, where it should be easy to hear the speech, to very loud, where it should be impossible to hear the speech.	You have a time limit to provide a response.	The computer will select a target score, which could range from one correct response to 10 correct responses. If you must achieve this hidden target to earn a reward voucher.

4.3. I. d. SiWN Reward Vs. No Reward. Experiment 5 employed the original SiWN task, as used in Experiment 2 and describes in detail in section 4.3. I. of this Methodological chapter. The task was altered slightly by the addition of reward vs. no reward conditions. The SiWN task encompasses the four within-group demand conditions: low, moderate, high and impossible. These were presented by Inquisit Experimental Generation Software in a systematically randomised order. The task also involved a between-group condition of reward vs. no reward. Participants in rewarded group, participants could receive an extra £2 in Amazon Vouchers in each of the listening tasks as an incentive for successful task performance. Whereas, participants in the no reward group would receive no incentive. Participants. Successful task performance was defined to participants as achieving at least 7 correct responses out of 10.

5. Data Analysis

5.1. Planned Contrasts

The specific predictions of Motivational Intensity Theory were tested using specific planned contrasts, which model the predictions of the theory. Therefore, planned contrasts which modelled a specific exponential increase in SNS activation as a function of task demand, while success is possible and justified, and as a function of success importance when demand is unknown, were used. Planned contrasts modelling an exponential decrease in PNS activation were also employed for the same predictions. Planned contrasts were also employed to test the specific MIT predictions for the measures of subjective effort and fatigue. Planned contrasts facilitate the sensitive testing of specific data patterns; for example, incremental increases in subjective effort as a function of demand. These specific data patterns could not be specifically measured using a standard ANOVA, which only demonstrates group differences, rather than specific pattern of group variances.

Planned contrasts were computed in RStudio mathematical software following the method outlined by Rosenthall and Rosnow (2006). Contrasts are the most appropriate and statistically powerful method of testing complex interactions in experimental designs (Rosenthal & Rosnow, 2006). The specific contrasts weights employed for each experiment are described within each respective methods section.

A potential disadvantage of planned contrasts is the fact that the weights employed must equal zero. This leads to a methodological flaw in relation to the predictions of motivational intensity theory. For example, for a listening task with low, moderate, high and impossible listening demand levels, the contrast weights -3, 1, 5, and -3 would be employed to test the prediction that effort increases incrementally as a function of task demand, and no effort occurs when the task is possible. These weights must be used to satisfy the requirements of the contrast equation. However, the model now predicts that effort in the low demand and impossible demand tasks should be equal; which may not be the case as individuals are likely to invest some effort in low demand tasks.

5.2. Likelihood Ratio

Likelihood ratios were employed as an alternative method of data analysis as they provide some advantages over traditional hypothesis testing, these include reduced influence of sample size on the interpretation (or misinterpretation) of statistical results. Furthermore, they enable comparative testing of two meaningful models, which enables the comparison of MIT to alternative and null hypotheses.

Likelihood ratios were used to test the predictions of motivational intensity theory against alternative models of effort mobilisation. This analysis was used in Experiment 2 to compare the likelihood that the physiological and self-report data occurred under a model that suggests effort increases as a function of task demand versus a model that suggests effort only increases as a function of demand while success is possible. The model that includes the possibility of success as a predictor of effort was also compared to a null model. The data from measures of self-reported effort and fatigue and the performance data was tested under a linear model versus a null model. The researcher followed the method outlined in Glover and Dixon (2004) and the correction procedure suggested by Hurvich and Tsai (1989) to control for model complexity. The ratios were computed in RStudio.

5.3. Correlations

Previous studies have found little evidence for relationships between physiological indicators of listening effort and the subjective experience of effort or fatigue felt by listeners (Alhanbali et al., 2017; Nachtegaal et al., 2009; Hornsby & Kipp, 2016; Hornsby 2013; Kramer et al., 2016). One explanation for the inconsistent data could be that objective and subjective fatigue are different constructs and relate to listening effort in complex ways dependant on differences in individuals and situational factors. Alternatively, the measures previously employed may not sensitively reflect physiological effort investment driven by changes in autonomic balance. It is important to test for these relationships as the emergence of listening effort and hearing fatigue in the hearing-impaired population is still poorly understood (McGarrigle et al., 2017a).

II. Experimental Chapters

1. Phase One: Experiments on Listening Demand

1.1. Introduction

If the investment of mental effort is governed by a necessity to conserve resources, individuals need to use information about a given task or activity to adapt the amount of effort dedicated to it. The ‘first’ prediction of MIT postulates that (listening) task demand directly determines effort; this ensures that individuals invest the minimum amount of effort required to attain success (Brehm, 1989). For instance, an easy task warrants little effort, a moderate task requires a little more and a challenging task utilises a lot of effort. The first study within this phase investigated the relationship between listening demand and effort-driven physiological responses guided by this first prediction of MIT. Secondly, MIT theorises that the positive relationship between demand and effort is not continual but limited by possibility of success (Brehm, 1989). This ensures that individuals will not waste resources by investing effort in an impossible task. Therefore, the second study within this phase investigated the relationship between listening demand and effort-driven physiological responses in both possible and impossible tasks. In both studies, the effects of listening demand on physiological responses driven by parasympathetic withdrawal and sympathetic activation were observed, as well as task performance and subjective reports of effort and fatigue.

Most of the current research on MIT has relied on Wright’s (1996) active coping hypothesis, in which he integrated the predictions of MIT with Obrist’s (1981) perspective. In doing so, Wright suggested that effort investment in cognitive tasks, where task outcome is dependent on task performance (for example, listening as determined by speech comprehension performance), is associated with beta-adrenergic driven myocardial sympathetic activity (Wright, 1996). Drawing on this approach researchers have been able to define 'effort' independently of the experimental manipulations, by adopting this perspective researchers investigating MIT can avoid circular reasoning. Circular reasoning becomes a problem if a researcher first validates a certain measure of effort, using the theoretical framework of MIT, by demonstrating that the measure changes as a function of task demand. Then if the researcher intends to test the MIT hypothesis that task demand determines effort and uses the same measures to quantify effort, one would engage in circular reasoning. To avoid both using MIT's hypothesised relationship between task demand and effort to demonstrate that the measure is a valid indicator of effort, and testing if task demand is a determinant of effort using the same measure as quantification of effort, researchers can separate their definition of effort from their experimental manipulations (Richter & Slade, 2017). Since Wright's conceptualisation researchers have examined the impact of task demand on beta-adrenergic driven myocardial sympathetic activity, using both SBP and PEP as indexes of this (Wright & Kirby, 2001). This approach has extended to a wide range of topics contributing to understanding how motivational factors can influence the relationship between task demand and effort investment. For example, implicit fear primes lead to greater PEP reactivity than implicit anger in easy tasks, while in difficult tasks the effect is reversed (Chatelain et al., 2016). Also, high self-focused attention was found to amplify SBP reactivity in difficult tasks (Silvia et al., 2010), and in another study participants with high need for closure showed increased PEP reactivity in difficult tasks (Richter et al., 2012). One study which only included a simple difficulty manipulation, without the inclusion of additional motivational factors, was conducted by Richter, Friedrich, and Gendolla (2008). They demonstrated that both SBP and PEP are determined by task difficulty while it is clear and fixed; both SBP and PEP reactivity increased across three possible levels of task difficulty (easy, moderate and difficult) but showed no reactivity in the impossible condition (Richter et al., 2008). This study provides straightforward evidence for MIT's predictions that effort increases as a function of task demand, only while success is possible.

Considering that most research on MIT has thus far incorporated Wright's (1996) active coping hypothesis it is unsurprising that it is almost exclusively focused on myocardial beta-adrenergic activity. Yet, whether this approach constitutes a holistic measure of effort in cognitive tasks is up for consideration. Many theoretical approaches highlight the influence of parasympathetic nervous system in the control of autonomic reactivity during effort investment. For example, studies on physical effort maintain that both ANS branches are involved in effort investment and both contribute variability at different intensity levels (Robinson et al., 1966; White & Raven, 2014). Bernstons's Autonomic Space Model also referenced this pattern of autonomic balance. The model suggests that changes in PNS and SNS activation can be reciprocal (as the PNS withdraws, the SNS dominates), non-reciprocal (both the PNS and SNS are active or neither are), or uncoupled (for example, PNS withdrawal alongside no change in SNS activity) (Berntson et al., 1991). Or in Porges (1995) polyvagal theory wherein, the parasympathetically mediated vagus nerve functions as a 'vagal brake'. The brake functions on a continuum that extends from inhibitory activity on the myocardium, reflected in decreased HR to facilitate resting states, to the reduction or removal of the 'brake' to facilitate the flight-or-flight response and mobilisation (Porges, 1995, 2007).

Studies on mental effort that have assessed myocardial PNS activity, usually as the high-frequency component of heart rate variability (RSA); have found that PNS withdrawal occurs during cognitively demanding tasks. For example, in a study conducted by Fairclough and colleagues (2005), participants were asked to perform an experimental task involving a multi-tasking framework at a low and high levels of difficulty. The results showed increased suppression of HF-HRV during task performance compared to baseline, and this suppression was more pronounced in the highly demanding task (Fairclough et al., 2005). In another study which used the same task at a high difficulty level, but sustained over 80 minutes comprising four 20-minute task periods, HF-HRV was significantly supressed in all four periods compared to baseline (Fairclough & Venables, 2006). Other research found that rMSSD (root mean square of the successive differences) derived heart rate variability (a time domain analysis considered to reflect PNS reactivity and has been correlated with HF-HRV) was suppressed during both working memory and sustained attention tasks relative to baseline (Hansen, Johnsen, & Thayer, 2003). These studies provide some evidence that the PNS is involved in the mediation of cardiac activity during effortful tasks. However, the studies that demonstrated a suppression of cardiac parasympathetic activity did not do so within the framework of MIT, so it is not possible to draw the conclusion that myocardial parasympathetic activity decreases as a function of task demand while task success is possible.

Interestingly, the measurement of parasympathetic activity has been used to an extent in the measurement of listening effort so far, with a handful of studies relying on measures of cardiac PNS activity during listening tasks. For example, the standard deviation of the R-R interbeat interval (SDRR) shows stronger reactivity with poorer sound-to-noise ratios and greater task complexity (Dorman et al., 2012; Seeman & Sims, 2015). However, overall variability of heart rate (HRV), which is under both PNS and SNS control, influences the SDRR thus causing it to be an invalid measure of parasympathetic reactivity. One study that used HF-HRV, a valid indicator of PNS activity, found that it decreased under the most difficult listening conditions for participants with hearing loss (Mackersie et al., 2015). However, although this provides us with information about PNS activity on the myocardium, these studies failed to measure SNS myocardial activity simultaneously, which is the focus of this research due to the theory-driven approach that emphases autonomic balance of myocardial activity.

The existing empirical literature on MIT, or SNS and PNS mediated effort investment does not provide strong or conclusive evidence in support of the hypothesis, due to a lack of studies which examined PNS and SNS myocardial activity simultaneously and within the framework of MIT. It is hypothesised that low to moderate listening effort should be characterised by strong reductions in myocardial PNS activity and slight increases in myocardial SNS activity, whereas high listening effort should be associated with complete myocardial PNS withdrawal and strong increases in myocardial SNS activity. A single listening effort study has assessed both SNS and PNS activity, in doing so Mackersie and Calderon-Moultrie (2016) observed that PNS withdrawal and SNS activity increased as the difficulty of a speech perception task increased. Although their quantification of PNS activity, HF-HRV, is reflective of myocardial reactivity, they used skin conductance to quantify SNS activity, which does not reflect SNS myocardial activity, thus the results do not provide evidence for the hypothesis. The first two studies presented in this thesis aim to address this gap in the literature by providing the first test of this integrative model of autonomic activity associated with listening effort.

1.2. Experiment 1: The relationship between listening demand and effort-driven cardiovascular responses

In accordance with the first prediction of MIT, a first study was conducted that examined both parasympathetic and sympathetic driven cardiovascular reactivity associated with effort in response to manipulated listening demand. The researchers predicted that listening effort (operationalised as ANS reactivity, specifically an exponential decay in PNS activity and an exponential increase in SNS activity) would increase as a function of the difficulty to understand speech (listening demand).

Additionally, it was expected that increased listening demand would induce higher ratings of subjective effort and fatigue as well as the reverse effect on task performance.

1.3. Method

1.3. I. Participants and Design. A sample of 87 adults, 57 females and 30 males (mean age 25.20 years), with no hearing impairment and no pacemaker participated for a 10-GBP Amazon voucher[1]. An initial pre-screening session was used to check for any anomalies in hearing within the sample (for details, see the procedure section). Each participant was then randomly allocated to one of three conditions of a speech recognition task: low, moderate or high listening demand.

1.3. II. Procedure. Computerised experiment generation software controlled the presentation of the task and collected the participant's responses (Inquisit by Millisecond Software, Seattle, WA). All participants took part individually. After providing informed consent, the participant completed a modified pure-tone audiometry assessment. The participant heard seven pure tones at 20dB and frequencies of 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 6000 Hz for 1 second each through headphones. The 0 dB reference values were determined in a calibration procedure by four individuals with good hearing (0 dB threshold for all frequencies in a standard pure-tone audiometry (British Society of Audiology, 2011).

[1]Sample size was determined using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) setting alpha error to 5%, beta error to 5% and f to 0.40.

After each tone, the participant indicated if they heard it or if they wished to repeat it by clicking an option on the computer screen ('yes', 'no' or 'repeat'). The researchers invited participants who identified a minimum of five tones to continue their participation and thanked those who did not for their time.

The researcher measured the participant's height and weight, and placed four pairs of disposable electrodes from a Cardioscreen 1000 impedance cardiograph (Medis Medizinische Messtechnik GmbH, Illmenau, Germany) on the left and right side of the participant's chest at the height of the xiphoid, and on the right and left side of the neck along the axillary lines. The Cardioscreen assessed an impedance cardiogram (ICG) and an electrocardiogram (ECG) at a sampling rate of 1000 Hz, for the measurement of PEP, RSA and HR. The researcher attached a blood pressure cuff from a Dinamap Carescape V100 monitor (GE Healthcare, Buckinghamshire, UK) to the participant's left arm. The monitor assessed systolic (SBP) and diastolic blood pressure (DBP) using the oscillometric method at two-minute intervals.

The participant indicated their age, gender, and completed ten practice trials of the Word Recognition Task (WRT). During the task, the participant wore headphones to listen to a target word spoken by a female voice and attempted to identify the target from four options on the computer screen. All the targets were common English words between three and nine characters in length. In the low listening demand condition, the participant heard a single target word. In the moderate condition, the participant received the target word in unison with one distractor word. In the high demand condition, the participant heard the target word alongside two distractor words. After each trial, a feedback message ('correct answer' or 'incorrect answer') appeared on the screen. After the practice trials, the participant received a score out of ten.

The participant could then read either a career magazine or a selection of journal articles for ten minutes. The experimenter measured cardiovascular activity via the Cardioscreen throughout this baseline period and recorded SBP and DBP at two-minute intervals during the last five minutes. The participant then completed a novel six-item fatigue questionnaire which addressed present feelings of fatigue using questions such as, “At this time, do you feel well rested?” and “How worn out are you currently?” The participant responded via a five-point Likert Scale where one represented "much less than usual" and five represented "much more than usual". See Appendix 2 for the questionnaire items. The participant then completed thirty trials of the WRT, in the same difficulty level as the practice task, hence task performance could range from zero to 30. The experimenter measured cardiovascular activity throughout the task and measured SBP and DBP at two-minute intervals during the first five minutes. Afterwards, the participant filled in the fatigue questionnaire for a second time and then completed a modified version of the NASA Task Load Index (NASA-TLX) (Hart & Staveland, 1988). The version contained two relevant subscales (mental demand and effort) from the original NASA-TLX. The participant responded using a five-point Likert scale, where one represented "very low" and five was “very high". The sum of responses from these two questions quantified total ‘effort’, thus subjective effort could range from two (lowest effort) to 10 (highest effort). After the questionnaire was completed, the researcher debriefed and remunerated the participant.

1.3. IV. Data Analysis. For the analysis of the ICG and ECG signals, the researcher used the data from last 5-minutes of each baseline period and the first 5-minutes of each task period. Myocardial sympathetic activity was quantified as PEP using the ICG and ECG signals collected from the Cardioscreen 1000 impedance cardiograph (Sherwood et al., 1990), the signals were then analysed offline in BlueBox analysis software (Richter, 2009). The interbeat interval (IBI) series for the baseline and task periods collected from the ECG were loaded into BlueBox where a peak finder located all R-Peaks. The researchers manually identified and corrected any missed, falsely identified peaks or ectopic beats, to produce an IBI series for the baseline and task periods. BlueBox averaged the dZ/dt signal derived from the ICG along with the ECG signal over periods of 60 seconds to create ensemble averages. Two independent raters scored PEP values (in milliseconds, computed as the interval between the onset of left ventricular depolarisation, indicated by the Q-point on the ECG, and the left ventricular ejection into the aortic valve, indexed by the B-point on the ICG) for each average. The interrater absolute agreement between these values was good (calculated using intraclass correlation (ICC) [2,1] >.97 for each period in each condition), so the mean of both rater's ensemble averages was used for the statistical analysis. The change score between task and baseline values of PEP determined the change in SNS. RSA quantified myocardial parasympathetic activity. The R-peaks of the ECG signal were detected offline in BlueBox (Richter, 2009). The resulting interbeat interval series was then loaded into Kubios analysis software (version 2.0, Biomedical Signal and Medical Imaging Analysis Group, University of Kuopio, Finland); using the Fast Fourier Transformation (FFT) technique, the high-frequency band (0.15 – 0.40 Hz) of heart rate variability (HF-HRV); which reflects RSA was calculated (Malik et al., 1996; Tarvainen, Niskanen, Lipponen, Ranta-aho, & Karjalainen, 2014). The mean HR was also calculated in BlueBox analysis software. The change score between task and baseline values of RSA determined the change in PNS activity.

To create a mean value of SBP and a mean value of DBP during the baseline and task, the researcher calculated the arithmetic mean of the recorded SBP and DBP values. The resultant change score between task and baseline values determined the changed in SBP and DBP. Changes in DBP and HR were used to verify that any observed changes in PEP resulted from increased sympathetic influence and not due to changes in cardiac preload or afterload (Sherwood et al., 1990). Increased preload, or amount of ventricular filling which occurs during diastole, stretches the myocardial fibres and therefore increases the force of myocardial contraction (via the Frank Starling mechanism). This shortens the length of PEP without any beta-adrenergic influence (Newlin & Levenson, 1979). HR can indicate cardiac preload; decreases in HR permit longer ventricular filling time and thus increase preload. Increased afterload, or aortic diastolic pressure, is the load against which the left ventricle contracts. The pressure in the left ventricle must exceed the pressure in the aorta for the aortic valve to open. If afterload increases, indicated by increased DBP (Obrist et al., 1987; Sherwood et al., 1990), the length of PEP increases because it takes longer for ventricular pressure to rise above the aortic pressure. Considering this, decreased PEP can only reflect increased sympathetic beta-adrenergic influence when accompanied by stable or increased HR and DBP (Richter et al., 2008). Decreases in either HR or DBP would indicate potential loading effects.

Of the six fatigue questionnaire items, three were positively framed. Thus, negative items were reverse scored, so that the higher the score on the fatigue questionnaire indicated increased subjective fatigue. Baseline and task fatigue scores could range from six (lowest fatigue) to 30 (highest fatigue). Change scores between task and baseline scores on the fatigue questionnaire indicated changes in subjective fatigue. Objective fatigue was quantified as mean response time on the WRT in milliseconds. Whereas, the sum of responses given on the two NASA-TLX items quantified subjective effort (ranging from two (lowest effort) to 10 (highest effort). The total number of correct responses determined task performance in response to listening demand.

Non-standard planned contrasts tested the specific predictions regarding myocardial autonomic activity. Contrast weights (-2.67; -0.66; 3.33), which model exponential growth, were used to test the prediction that SNS increases exponentially as a function of listening demand. Contrast weights (3.33; -0.66; -2.67), which model exponential decay, tested the prediction that PNS activity decreases exponentially as a function of listening demand. Linear contrasts tested the effect of listening demand on total autonomic activity (the sum of PEP and RSA change scores

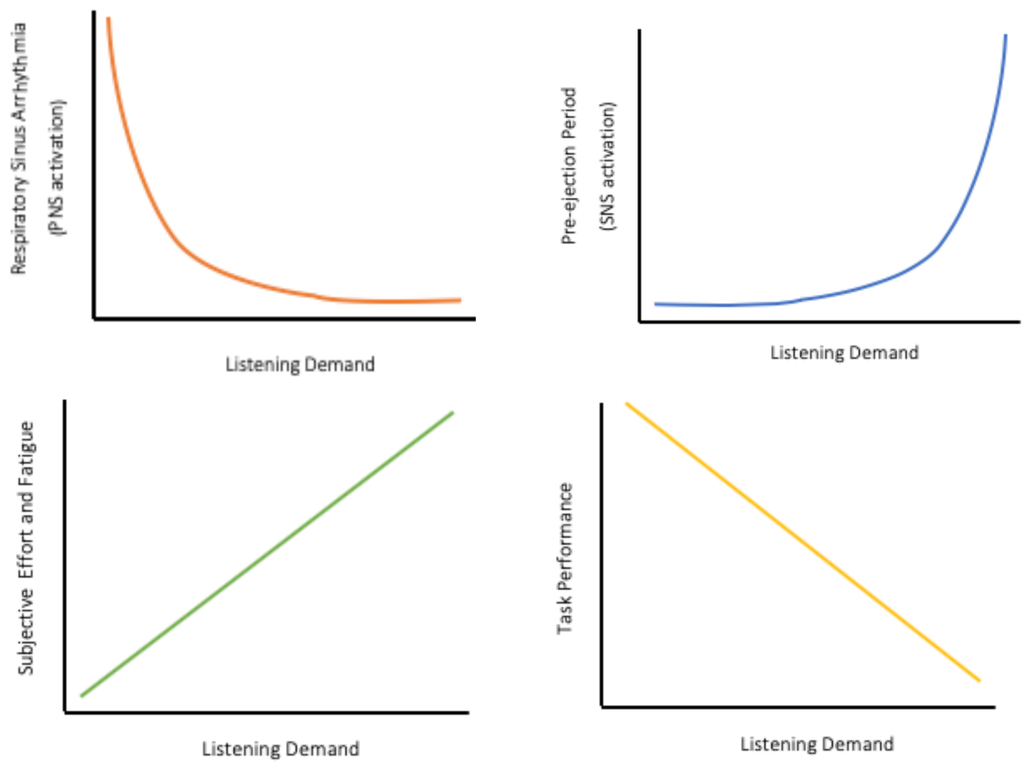

Figure 8.

A figure illustrating the hypothesised effects for the key parameters. SNS activation is hypothesises to increased exponentially as a function of listening demand. Similarly, PNS activation is hypothesised to decrease exponentially. Subjective effort and fatigue are expected to increase linearly as a function of demand, while task performance should decrease.

after standardisation[2]), subjective effort and fatigue, and task performance.

1.4. Results

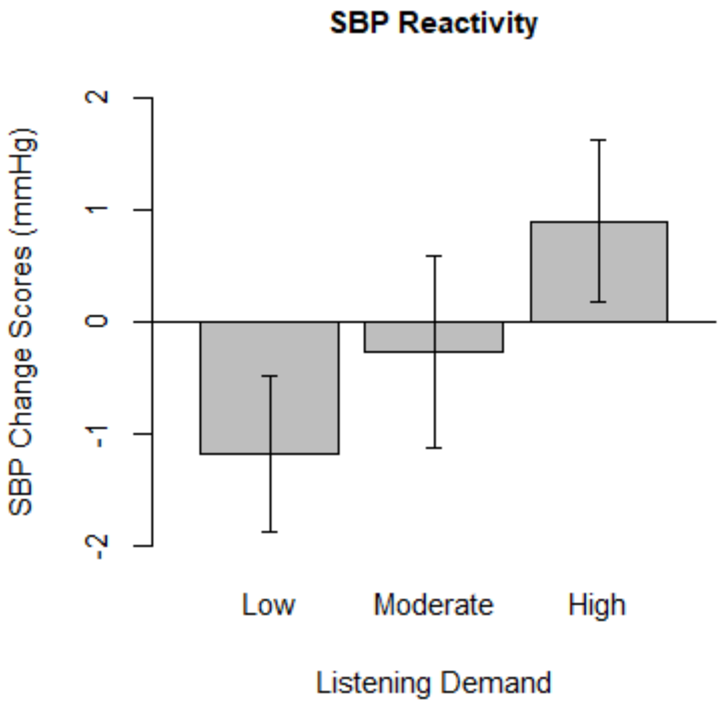

Figure 9.

Mean SBP Change Scores in the Listening Demand Conditions of the WRT (Low vs. Moderate vs. High). Error Bars Represent Standard Error. SBP Indicates Systolic Blood Pressure.

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[2] PEP and RSA scores were standardised by dividing the raw change scores by the standard deviation. The resulting values were added together and then multiplied by -1 to shift the direction from negative to positive so that increased ANS activity would be represented by the more positive values.

1.4. I. Planned Contrasts: Analysis 1.

1.4. I. a. Cardiovascular Response. Planned contrasts revealed no significant effects on PEP reactivity, $t(84) = 0.16$, $p = .44$, showing no significant exponential increase in sympathetic activity (operationalised as PEP) occurred in response to listening demand. Additionally, the contrast tests revealed no significant effects on RSA, $t(84) = 0.05$, $p = .48$, meaning there were no significant exponential decreases in parasympathetic activity in response to listening task demand. However, planned contrasts revealed a significant effect of listening demand on SBP, $t(84) = 1.92$, $p = .03$, Figure 9 displays this pattern. Although there were no significant effects for PEP and RSA, significant increases in SBP suggest that cardiac activity increased exponentially in response to listening demand. Linear contrasts showed that there was no significant effect of listening demand on total autonomic activity, $t(84) = -0.09$, $p = .46$. Linear planned contrasts of HR and DBP (used as controls) were not significant (*ps* > .10). The mean change scores and standard errors of all cardiovascular parameters can be found in Table 6.

Table 6.

Change Score Means and Standard Errors (in Parentheses) of Cardiovascular Responses During the Three Listening Demand Conditions of the WRT.

	Low Demand	Moderate Demand	High Demand
HR	-0.81 (0.96)	-0.52 (0.59)	0.50 (0.56)
DBP	0.40 (0.76)	-0.07 (0.52)	-0.08 (0.69)
SBP	-1.18 (0.70)	-0.28 (0.86)	0.90 (0.72)
RSA	-3.39 (2.82)	2.14 (2.56)	-4.94 (1.66)
PEP	-0.38 (0.51)	-0.17 (0.57)	-0.23 (0.53)
ANS	0.33 (0.24)	0.05 (0.29)	0.37 (0.21)

1.4. I. b. Subjective and Performance Measures. Linear contrasts revealed that there was no significant effect of listening demand on subjective ratings of fatigue $t(84) = -0.85$, $p = .20$. However, the linear contrast demonstrated a significant effect of listening demand on subjective effort $t(84) = 11.70$, $p < .001$, suggesting that while the participants did not experience fatigue they felt the more demanding conditions required more mental effort. The mean change scores and standard errors of all subjective ratings are given in Table 7. The linear contrast for objective fatigue revealed that listening demand had a significant effect on response latency (in seconds) $t(84) = 2.76$, $p = .003$. This result demonstrates that participants took longer to respond in the most demanding listening task indicative of objective fatigue: Low (M = 1.17, SE = 0.43), Moderate (M = 1.09, SE = 0.41) and High (M = 1.35, SE = 0.50). Linear contrasts revealed a significant effect of listening demand on speech recognition scores $t(84) = 11.21$, $p < .001$. Indicating that task performance decreased over the three demand conditions: Low (M = 30, SE = 0.00), Moderate (M = 29.41, SE = 0.16) and High (M = 25.31, SE = 0.49).

Table 7.

Change Score Means and Standard Errors (in Parentheses) of Self-Reports During the Three Listening Demand Conditions of the WRT.

	Low Demand	Moderate Demand	High Demand
Effort	2.66 (0.22)	5.24 (0.29)	7.24 (0.31)
Fatigue	1.93 (0.56)	0.52 (0.51)	1.28 (0.57)

Note: Change scores between task and baseline values (after reverse scoring) on the fatigue questionnaire quantified fatigue. The sum of responses given on the two NASA-TLX items quantified subjective effort.

1.4. II. Analysis 2. Although the contrast analysis of performance showed that listening demand had a significant effect on the number of correct responses, suggesting successful manipulation of task demand, data from the descriptive statistics indicates otherwise. Mean task performance scores show that the low and moderate conditions did not differ in task demand: low (M = 30, SE = 0.00), moderate (M = 29.41, SE = 0.16), so the scores were collapsed over the low and moderate conditions. An independent samples *t*-test then compared cardiovascular and subjective responses in the collapsed low demand condition (low 2) and the high demand condition.

1.4. II. a. Cardiovascular Response. The analysis of PEP reactivity in response to task demand remained not statistically significant $t(85) = -0.73$, $p = .47$. However, there was a significant difference in RSA change scores between the low 2 and high demand conditions $t(82) = 1.70$, $p = .04$, Figure 10 displays this pattern. Levene's test indicated unequal variances $F = 7.29$, $p = .008$, so degrees of freedom were adjusted from 85 to 82. Demonstrating a withdrawal of PNS activity in the high demand condition, which is suggestive of effort mobilisation. SBP activity remained significant, $t(85) = -1.74$, $p = .04$, demonstrating increased cardiovascular reactivity in the high demand condition. The effect of listening demand on total ANS activity remained non-significant $t(85) = -0.58$, $p = .28$. The analysis of HR and DBP (used as controls) remained non-significant (*ps* > .10). The mean change scores and standard errors of all cardiovascular parameters can be found in Table 8.

Table 8.

Change Score Means and Standard Errors (in Parentheses) of Cardiovascular Responses in the Demand Conditions of the WRT.

	Low 2 Demand	High Demand
HR	-0.67 (0.56)	0.50 (0.56)
DBP	0.17 (0.46)	-0.80 (0.69)
SBP	-0.73 (0.55)	0.90 (0.72)
RSA	-0.63 (1.92)	-4.94 (1.66)
PEP	-0.51 (0.50)	0.38 (0.57)
ANS	0.19 (0.19)	0.37 (0.21)

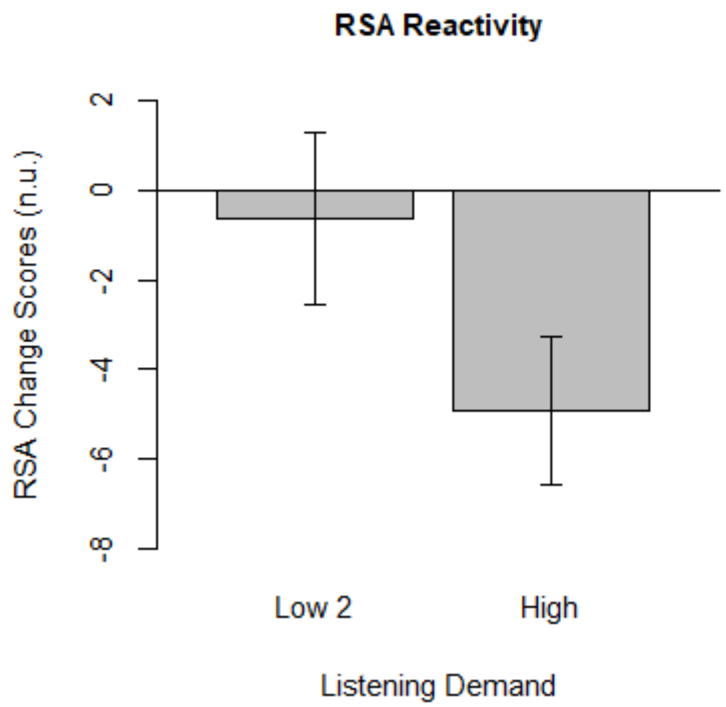

Figure 10.

Mean RSA Change Scores During the Low 2 and High WRT Conditions. Error Bars Represent Standard Error. RSA Indicates Respiratory Sinus Arrhythmia.

1.4. II. b. Subjective and Performance Measures. The difference between subjective fatigue ratings in the low 2 (M = 1.22, SE = 0.39) and high (M = 1.28, SE = 0.57) conditions remained not significant, $t(85) = -0.08$, $p = .47$. As in analysis 1, there was a significant difference in the effort ratings between the low 2 (M = 3.95, SE = 0.25) and high (M = 7.24, SE = 0.31) demand conditions $t(85) = -7.92$, $p < .001$. There was a significant difference in the response time between the low 2 and high listening demand conditions, $t(85) = -3.91$, $p < .001$. Indicating that, as in analysis 1, the participants were slower in responding during the task in the most demanding listening condition: low 2 (M = 1.13, SE = 0.30) and high (M = 1.35, SE = 0.50), suggestive of objective fatigue in response to listening demand. The difference between the total number of correct responses in the low 2 (M = 29.71, SE = 0.09) and high (M = 25.31, SE = 0.49) demand conditions remained significant $t(29.88) = 8.89$, $p < .001$.

1.5. Discussion

1.5. I. Physiological Findings. The initial analysis of the data from this study found no evidence for increased SNS activation or PNS withdrawal as a function of listening demand, as indicated by PEP and RSA. Furthermore, when combining the data from these parameters to calculate overall ANS activity, the analysis suggested that ANS reactivity did not change in response to listening task demand. However, SBP increased over the three demand conditions. This finding is consistent with many studies on mental effort that have shown SBP to reliably respond to manipulations of task demand (Richter et al., 2008), demonstrate anticipatory effort (Contrada, Wright, & Glass, 1984; Wright, Contrada, & Patane, 1986), and show the effect of mood on effort (Gendolla & Krüsken, 2002). For many years, researchers employed SBP as the main indicator of sympathetic activity on the cardiac system. SNS-driven beta-adrenergic activity and its resultant impact on myocardial contractility influences SBP. The more forceful the contraction, the higher the cardiac output, which influences the maximum arterial pressure following a heartbeat (SBP). So, one could assume that myocardial SNS activity caused the increases in SBP in this study, consistent with aforementioned experiments that also found task demand effects on SBP. However, SBP is not only influenced by beta-adrenergic SNS myocardial activity, thus it is not a pure measure of effort investment as defined by Wright's active coping hypothesis (Wright, 1996). Blood pressure changes can also be driven by variations in heart rate and total peripheral resistance, which are not exclusively under beta-adrenergic control (but also counteracting beta-adrenergic vasodilatory and alpha-adrenergic vasoconstrictive activity). Understanding this about SBP may explain the discrepancy between the PEP and SBP data in this study. PEP is the 'gold standard' in non-invasive cardiovascular indicators of beta-adrenergic SNS activity, due to its essentially exclusive reliance on the force of myocardial contraction. Therefore, if effort-related SNS activity caused the changes in SBP, then one would expect the same pattern for PEP.

Drawing on the descriptive statistics, PEP decreased in the moderately demanding listening task possibly reflecting effort investment. Whereas, the minimal PEP change in the highly demanding listening task could indicate disengagement, due to intolerable demand levels or lack of justification for effort investment. As predicted by MIT, when a task is too hard or not worth doing then individuals will 'give up'. However, the RSA data demonstrates a contrasting pattern with the largest decreases occurring in the listening tasks with a low and high demand, suggesting the highest PNS withdrawal in response to the highly demanding listening task due to effort investment. The descriptive data from the measures of PEP, RSA and SBP are clearly contradictory, thus drawing compelling conclusions regarding effort-driven autonomic activity on the myocardium in response to listening demand is unfeasible.

The performance data suggests that the manipulation of listening demand may not have been successful, which provides a plausible explanation for the lack of significant physiological findings in this study. Although the planned contrast suggested that increased listening demand significantly decreased task performance, the mean scores in both the low and moderate conditions differed by only 0.59 and indicated practically perfect performance in these tasks. Even in the highly demanding task, the average score was just shy of 85%. Alternative studies on listening effort have suggested that sentence intelligibility tests or speech reception thresholds that produce a 50% correct performance standard are best used to represent a highly demanding listening situation (for examples see: Koelewijn, de

Kluiver, Shinn-Cunningham, Zekveld, & Kramer, 2015; Kramer, Teunissen, & Zekveld, 2016; Pichora-Fuller & Singh, 2006; Winn, Edwards, & Litovsky, 2015; Zekveld, Rudner, Kramer, Lyzenga, & Rönnberg, 2014). Studies also indicated that performance standards at around 80% are suggestive of easy listening demand (Koelewijn, Zekveld, Lunner, & Kramer, 2018). Because of this, the researcher decided to collapse the data from the low and moderate conditions (low 2) and compare it to the high listening demand condition. The resulting statistical analysis indicated that RSA significantly decreased from the low 2 to the high listening demand condition. This finding may indicate the beginning of parasympathetic withdrawal and thus minimal-moderate effort investment in the listening task, this pattern of PNS withdrawal has been well documented in research on physical effort (Michael, Graham, & Oam, 2017). The decreases in RSA found in this analysis is coherent with findings from other mental workload research that demonstrated consistent decreases in parasympathetic-driven HRV in response to increasingly difficult *n*-back tasks (Lenneman & Backs, 2009; Mandrick, Peysakhovich, Rémy, Lepron, & Causse, 2016); the maximum *n*-back used in these studies was a 2-back, suggestive that decreases in RSA occur with minimal-moderate demand. The evidence found in this study for PNS withdrawal during minimal-moderate effort investment, provides further evidence that the manipulation of task demand in this study was unsuccessful.

1.5. II. Subjective Measures and Performance Data. The initial planned contrast revealed that participant's subjective ratings of effort increased as a function of listening demand, and this significant result remained in the second statistical analysis. It is often the case in research that objective and subjective rating of effort differ (for example Seeman & Sims, 2015). This may be due to potential bias in the participant's responses, or a disparity between experiencing a feeling of effort and the objective indicators of effort in cardiovascular reactivity. Additionally, subjective fatigue did not show the same increase in response to task demand as subjective effort. In fact, the highest fatigue response occurred during the low listening demand condition. Participants may have reported tiredness due to feeling bored which can have similar emotional characteristics to fatigue (McGarrigle et al., 2017b; Pattyn, Neyt, Henderickx, & Soetens, 2008); increases in boredom during this condition would also support the idea that the task was too easy and the demand manipulation was unsuccessful.

Although the high-performance standard in all demand conditions indicates that the task was too simple to be effortful, it is noteworthy that effort is not always reflected in task performance. One could invest high effort in order to maintain a high-performance standard, or the same high performance standard could be achieved through minimal effort if the task was easy. Furthermore, one could invest a lot of effort and perform inadequately due to intense difficultly; similarly, one could invest no effort and perform poorly due to 'giving up'. Furthermore, it has been suggested that performance standard could be maintained due to a masking effect, when other aspects of the task are compromised in order to maintain the overarching goal (Hockey, 2011). This study found some evidence for this idea, in that participants took longer to respond in the more demanding tasks, indicative of objective fatigue. Still, speech comprehension is an essential component in audiology assessments, as it is imperative for adapting hearing aids and ensuring individuals can perceive sounds successfully. Therefore, researchers should not avoid the use of performance data in laboratory studies on listening effort. However, the reliance on speech comprehension highlights the potential issue in audiological assessment; individuals may correctly perceive speech at the expense of high-sustained effort that would not be considered during the hearing assessment.

1.5. III. Directions for future studies. This study although with limitations provided valuable information to direct future studies within this PhD. The listening task designed for use in this study aimed to provide an objective manipulation of listening demand. Yet, considering the task characteristics, particularly in the easy condition involving single word identification, it is probable that although objectively increasing in difficulty, the conditions did not differ enough to prompt the need for effort investment. Furthermore, it was not overlooked that the task did not provide the most ecologically valid manipulation of listening demand, since only single words were presented. Listening tasks used in previous research that comprised sentence in noise stimuli (for example, Zekveld et al., 2010) are possibly more representative of speech recognition in daily life. Furthermore, changes in cardiac reactivity are slow, thus the period of invested effort required to hear a word presented for less than a second was possibly insufficient to induce a cardiac response. It was with this in mind that the future studies within this PhD would employ an alternative listening task with more ecologically valid stimuli. Additionally, during the baseline period within this first study, the participants read a magazine and, although minimal, this required some degree of motor activity. Therefore, in order to have more control over the physiological measures, the researcher also modified this for future studies. Lastly, MIT predicts that effort occurs as a function of demand as long as the effort is justified. It is possible that the participants felt no justification to invest effort, as there was no incentive to do so; future studies aimed to amend this.

2. Experiment 2: The limiting effect of the possibility to understand speech on the relationship between listening demand and effort-driven cardiovascular responses

The aim of this second experiment was to investigate the limiting effect of the possibility to understand speech on the proportional relationship between listening effort and listening demand. MIT suggests that effort occurs as a function of task demand when success is both possible and justified. According to the theory, no effort should be mobilised in an impossible task because there is no chance of success. This upper limit of the demand-effort relationship ensures one does not waste effort on futile tasks in accordance with the predisposition to conserve energy. Therefore, it was predicted that ANS activity (reflected in PNS withdrawal and SNS dominance) would increase as a function of listening demand while success was possible, and would show no response when success was unachievable.

2.1. Method

2.1. I. Participants and Design. A sample of 45 adults, 26 females and 19 males (mean age of 24.87 years), without pacemakers and normal hearing participated[3]. The same pre-screening measure as used in Experiment 1 checked the participants' hearing threshold; those identifying five or more tones were eligible to take part. Emails, social media, and advertisement posters displayed at Liverpool John Moores

[3] Sample size was determined using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) setting alpha error to 5%, beta error to 5% and f to 0.25.

University recruited the sample. All participants completed four listening demand conditions of a speech recognition task: low, moderate, high or impossible.

2.1. II. Procedure. As in Experiment 1, Inquisit by Millisecond Software (Seattle, WA) controlled the presentation of all stimuli and collected participant's responses. Each participant took part individually and provided informed written consent. The researcher measured the height and weight of the participant and employed the same physiological measures in this experiment as were used in Experiment 1. Four pairs of electrodes from the Cardioscreen 1000 attached to the left and right side of the participant's chest and neck measured an ICG and ECG at a sampling rate of 1000 Hz, for the measurement of PEP, RSA and HR. A blood pressure cuff from a Dinamap Carescape V100 monitor attached to the participant's upper left arm assessed SBP and DBP using the oscillometric method at two-minute intervals. The researcher assessed HR and DBP to control for changes in cardiac preload and afterload.

The researcher verbally explained the experimental tasks and structure. The participant then indicated their age, gender, and completed a novel 9-item fatigue questionnaire (see appendix 3 for the questionnaire items). For each item two comparative adjectives were presented on the screen, and the participant selected the word which best described their current state. Three words for fatigue (fatigued, tired, worn out) and three words for alertness (energised, lively, well rested) were displayed in all possible combinations to create nine items. After this, the participant completed two practice trials of one of four demand conditions of a speech in pure white noise task (SiWN) to allow the acquisition of information about task demand. Inquisit presented the four conditions in a random order to each participant, and each condition contained two practice and ten task trials. A trial of the SiWN required participants to listen via headphones to a 32-second short story spoken by a female voice, in the presence of white noise. The speech was presented at 50dB. The decibel level of the white noise for each condition was determined in a calibration procedure by seven individuals with normal hearing. The white noise in the low demand condition was presented at -36dB lower than the speech, at -15dB in the moderate condition, at -9dB in high demand condition, and at +3dB higher than the speech in the impossible demand condition. After hearing the audio, the participant had 5 seconds to respond to a multiple choice comprehension question (for examples of the short stories and comprehension questions used please see appendix 4). After each practice trial, the participant received feedback ('correct answer' or 'incorrect answer'). The participant then undertook a 6-minute baseline period in which they viewed a clip from the nature documentary 'Kingdom of Plants'. The researcher measured cardiovascular activity using ECG and ICG signals throughout this period and recorded the SBP and DBP values at two-minute intervals after 60 seconds. The participant then completed ten task trials of the SiWN, in the same difficulty level as the practice trials; thus, listening performance could range from 0 - 10. The participant was informed that seven or more correct responses would earn them a £5 Amazon Voucher. Throughout the task trials, the researcher measured cardiovascular activity using ECG and ICG signals and recorded SBP and DBP values at two-minute intervals. After completing the task, the participants completed two questionnaires. They completed the 9-item fatigue questionnaire for a second time, to measure their post-task fatigue. The participant then completed the modified version of the NASA Load Index (NASA-TLX) (Hart & Staveland, 1988), as in Experiment 1, to quantify subjective effort. After the participant completed all four conditions, the researcher debriefed and remunerated them.

2.1. III. Data Analysis. The quantification of myocardial sympathetic activity as PEP followed the same procedure as in Experiment 1. Two independent raters scored PEP values and because the interrater agreement was good (ICC [2,1] > .98), the arithmetic mean of both raters' PEP values was used for the statistical analyses. The change score between task and baseline values of PEP determined the change in SNS activity. Similarly, the quantification of myocardial parasympathetic activity as RSA remained the same as in Experiment 1. The change score between task and baseline values of RSA determined the change in PNS activity. Total ANS[4] activity was calculated as in Experiment 1. The mean HR was collected from the Kubios analysis software and SBP and DBP values recorded during the baseline and task were averaged to create a mean value of SBP and a mean value of DBP during the baseline and during the task. The change score between task and baseline values for HR, SBP and DBP were then calculated. For the 9-item fatigue questionnaire, a score of '1' was given each time the participants clicked on words that represented 'fatigue', whereas words that represented 'alertness' were scored as '0'. Therefore, fatigue questionnaire ratings could range from 0-9, and the change between task and baseline scores indicated subjective fatigue. Response time in seconds quantified objective fatigue. The sum of responses given on the two NASA-TLX items quantified subjective effort and the total number of correct responses in each condition determined task performance.

[4] PEP and RSA scores were standardised by dividing the raw change scores for each condition by their standard deviation. The sum of the resulting values (PEP + RSA) was multiplied by -1 to shift the direction from negative to positive so that increased ANS activity would be represented by the more positive values.

Planned contrasts were applied to test the hypotheses about the impact of listening demand on cardiac response and subjective ratings of effort and fatigue. The four conditions were assigned the following contrast weights: Low Demand -2, Moderate Demand 0, High Demand 4, and Impossible Demand -2, in order to model the predictions of MIT in relation to SNS activity. Whereas, for PNS activity, contrast weights which modelled an exponential decay were used (2.5, -1.5, -3.5, 2.5). For the other analyses of, total autonomic activity, subjective effort and fatigue the contrast weights (-3, 1, 5, -3) were used, as these model a linear increase and disengagement in the impossible task. Task performance and response times were testing using a linear contrast.

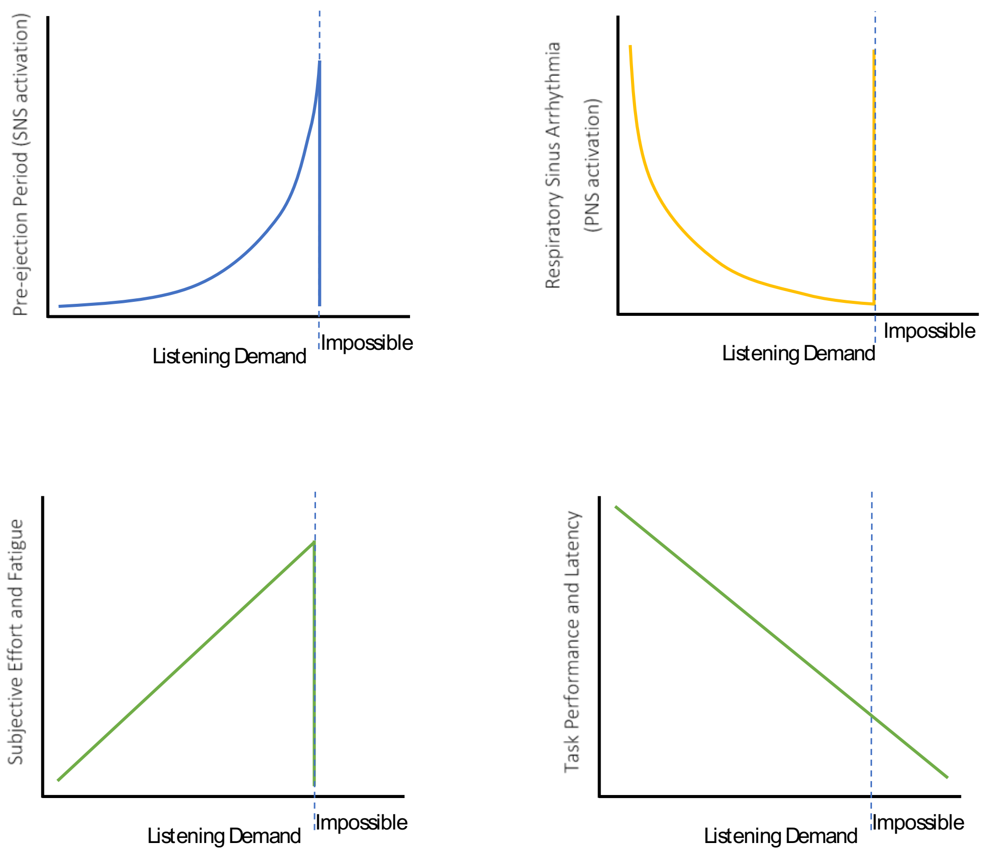

Figure 11.

A figure illustrating the hypothesised effects for the key parameters. SNS activation is hypothesises to increased exponentially as a function of listening demand while task success is possible. Similarly, PNS activation is hypothesised to decrease exponentially while the task is possible. Subjective effort and fatigue are expected to increase linearly with demand while the task is possible. A linear decrease as a function of task demand is predicted for task performance.

In addition to the contrast analysis, likelihood ratios evaluated the probability of the data occurring under one model of effort compared to the probability of the data occurring under a second model. The researcher followed the method outlined in Glover and Dixon (2004) and revisited in Richter (2016) to calculate likelihood ratios and control for model complexity.

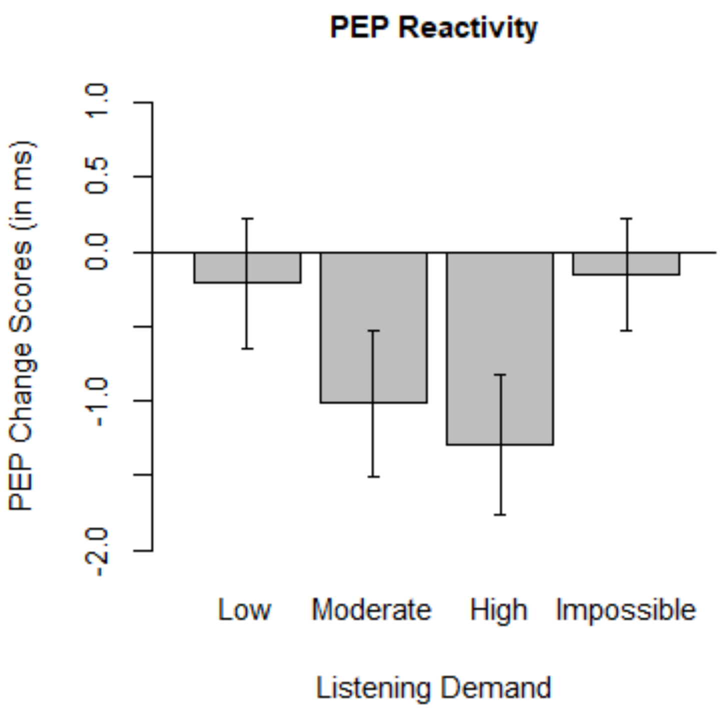

Figure 12.

Mean PEP Change Scores During the SiWN task. Error Bars Represent Standard Error. PEP Indicates Pre-Ejection Period.

2.2. Results

2.2. I. Planned Contrasts.

2.2. I. a. Cardiovascular Response. Planned contrasts revealed that there was no significant effect of listening demand on RSA, $t(44) = 1.03$, $p = .15$. Indicating that there was no significant difference in PNS activity, operationalised as RSA in the four demand conditions. Nor was there a significant effect of listening demand on SBP, $t(44) = 0.06$, $p = .48$. Yet, there was a significant effect of listening demand on PEP-q responses, $t(44) = 2.14$, $p = .02$, see Figure 12. This result indicates that increased listening demand resulted in increased SNS activity (reflected in decreased PEP) up until the point at which the task was no longer possible, at this point SNS activity decreases. The analysis of DBP (used as a control) was not significant, $t(44)$, = 1.11, $p = .14$. The planned contrast for HR was significant, $t(44) = 2.50$, $p = .008$, indicating an increase in HR during the moderate and high listening demand levels compared to the easy and impossible tasks. Since DBP remained unchanged and the HR level increased, it was assumed that neither preload nor afterload affected the change in PEP. The contrast analysis of total ANS activity was also not significant, $t(44) = 0.92$, $p = .18$. The mean change scores and standard errors of all cardiovascular parameters can be found in Table 9. Scatterplots in Figure 13 and 14 display the individual differences in PEP and RSA reactivity throughout the four listening conditions.

Table 9.

Change Score Means and Standard Errors (in Parentheses) of Cardiovascular Responses During the Four Listening Demand Conditions of the SiWN.

	Listening Demand			
	Low	Moderate	High	Impossible
HR	2.88 (0.47)	4.16 (0.55)	3.76 (0.57)	2.47 (0.43)
DBP	1.20 (0.66)	1.79 (0.61)	1.67 (0.59)	0.80 (0.58)
SBP	2.21 (0.70)	1.31 (0.72)	1.33 (0.74)	0.36 (0.58)

RSA	-3.42 (1.83)	-0.54 (1.72)	-2.28 (1.57)	-3.36 (1.45)
PEP	-0.21 (0.44)	-1.02 (0.49)	-1.29 (0.47)	-0.15 (0.38)
ANS	0.35 (0.20)	0.36 (0.19)	0.63 (0.21)	0.41 (0.20)

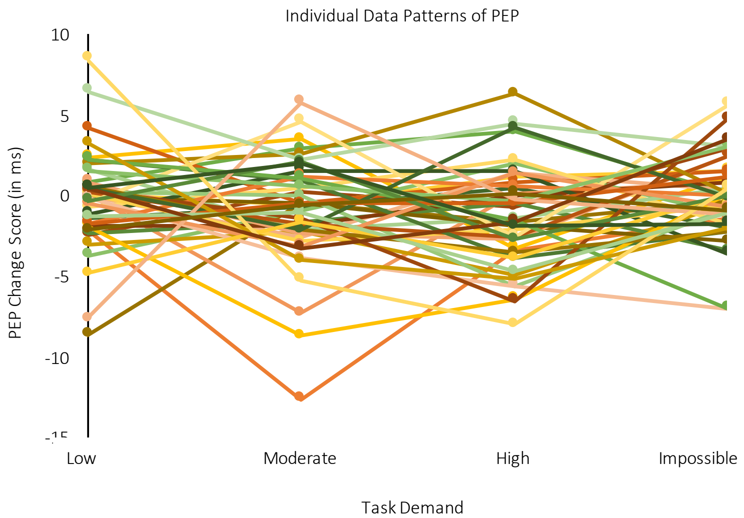

Figure 13.

Change Score Means and Standard Errors (in Parentheses) of Cardiovascular Responses During the Four Listening Demand Conditions of the SiWN.

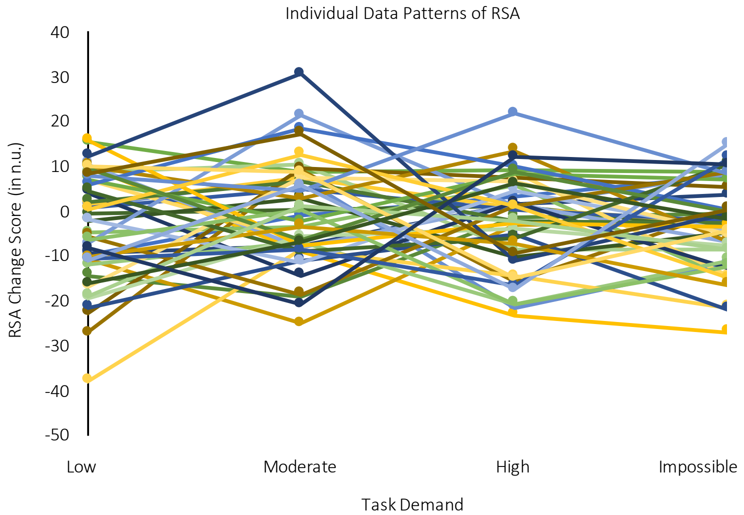

Figure 14.

Change Score Means and Standard Errors (in Parentheses) of Cardiovascular Responses During the Four Listening Demand Conditions of the SiWN.

2.2. I. b. Subjective Measures and Performance. The contrast analysis revealed that listening demand did not have a significant effect on self-reported fatigue, $t(44) = 0.70$, $p = .24$. Whereas, planned contrasts revealed a significant effect of listening demand on both self-reported effort $t(44) = 6.70$, $p < .001$, task performance $t(44) = 22.60$, $p < .001$ and task response time $t(44) = 10.20$, $p < .001$. This indicates that the participants rated their effort investment to increase with task demand while the task was possible. In the impossible condition, this effort rating is lower indicative of task disengagement. Additionally, the performance decrement indicated that participant's performance decreased and became less efficient as a function of listening demand. The low task score and the longest response time seen in the impossible condition may demonstrate task disengagement, as predicted by MIT, and objective fatigue. It is of note that when tested under a linear contrast, listening demand had a significant effect on subjective fatigue, $t(44) = 2.85$, $p = .003$.

Table 5.

Change Score Means and Standard Errors (in Parentheses) of Self-Reports and Task Performance During the Four Listening Demand Conditions of the SiWN.

	Listening Demand			
	Low	Moderate	High	Impossible
Subjective Effort	4.18 (0.29)	6.71 (0.28)	8.33 (0.20)	7.93 (0.41)
Subjective Fatigue	0.87 (0.60)	1.58 (0.61)	2.11 (0.58)	2.51 (0.54)
Task Performance	9.67 (0.10)	7.87 (0.18)	7.62 (0.24)	2.73 (0.28)
Response Latency (in seconds)	2.00 (0.80)	2.23 (0.10)	2.43 (0.95)	3.46 (0.15)

2.2. II. Likelihood Ratios. Likelihood ratios further tested the predictions of motivational intensity theory against alternative models of effort mobilisation. This analysis compared the likelihood that the physiological and self-report data occurred under a model that suggests effort increases as a function of task demand versus a model that suggests effort only increases as a function of demand while success is possible. The model that includes the possibility of success as a predictor of effort was also compared to a null model. The data from measures of self-reported effort and fatigue and the performance data was tested under a linear model versus a null model. The researcher followed the method outlined in Glover and Dixon (2004) and the correction procedure suggested by Hurvich and Tsai (1989) to control for model complexity.

2.2. II. a. Cardiovascular Response. The analysis of PEP-q reactivity data compared the likelihood of the data occurring under the prediction that effort-related SNS activity increases exponentially as a function of demand when success is possible, against an alternative hypothesis that omitted the possibility of success as a limiting factor in the effort-demand relationship. The resulting likelihood ratio ($\Lambda = 2.02$) provided weak evidence in favour of the MIT model according to the classification criteria proposed by Royall (1997). This indicated that the impossible task was more likely to cause disengagement rather than an increase in effort. However, the analysis also found weak evidence in favour of the null hypothesis (Λ = 4.91) over that predicted by MIT. For RSA, the calculated ratio (Λ = 1.19) indicated weak evidence in favour of MIT over the prediction of an exponential decay in RSA regardless of the possibility of success. However, moderate evidence supported the null hypothesis (Λ = 9.09) over MIT for RSA reactivity.

2.2. II. b. Subjective Measures and Performance. According to MIT, self-reported effort should increase as a function of demand while task success is possible. This model was tested against an alternative hypothesis that self-reported effort increases with demand even when success becomes impossible. The likelihood ratio (Λ = 2702.70) provided strong evidence in favour of the alternative model. Both models were also tested against the null hypothesis of no effect of task demand on effort. The corrected ratio (Λ = 5.22) indicated weak evidence in favour of MIT over the null model. Whereas, strong evidence was found in favour of the alternative model which predicts a linear relationship between effort and task demand over the null hypothesis (corrected Λ = 14189.78). The fatigue data was also tested under MIT's hypothesis and the alternative linear model. The ratio (Λ = 3.52) in favour of the alternative model indicated weak evidence in support of a linear relationship between listening demand and subjective fatigue. Both models were tested against the null hypothesis of no effect and in both cases, the likelihood ratio provided evidence in favour of the null hypothesis. The corrected ratio (Λ = 9.76) provided strong evidence in favour of the null hypothesis over MIT's predicted model and weak evidence (Λ = 2.77) in favour of the null hypothesis over the linear model. Likelihood ratio tests also indicated strong evidence in favour of the linear model that predicted performance would show a linear decrease as a function of task demand, regardless of the possibility of success. The data was found to be much more likely to occur under the linear model than the null model of no effect (Λ =

23256374216). Additionally, likelihood ratios provided strong evidence (Λ = 283866611833) in favour of a linear model that predicted a performance decrement in reaction time as a function of demand when compared to the MIT hypothesis. Please see table 10 for a summary of the measures and their likelihood ratio's under the tested models.

Table 10.

A table listening the measures employed in this study and the observed likelihood of the data from the measures occurring under three comparable models: 1) MIT (increases as a function of demand only while success is possible, and disengagement when impossible); 2) Linear (increases as a function of demand only); 3) Null (no effect).

	MIT	Linear (task demand only)	Null
PEP	Weak evidence for MIT over Linear. Λ = 2.02.	Evidence for MIT and Null stronger.	Weak evidence for Null over MIT. Λ = 4.91.
RSA	Weak evidence for MIT over Linear. Λ = 1.19.	Evidence for MIT and Null stronger.	Strong evidence for Null over MIT. Λ = 9.09.
Subjective Effort	Weak evidence for MIT over Null. Λ = 5.22.	Strong evidence for Linear over MIT. Λ = 2702.70. Strong evidence for Linear over Null. Λ = 14189.78.	Evidence for MIT and Linear stronger.
Subjective Fatigue	Evidence for Null and Linear stronger.	Weak evidence for Linear over MIT. Λ = 3.52.	Strong evidence for Null over MIT. Λ = 9.76. Weak evidence for Null over Linear. Λ = 2.77.

Task Performance	Not predicted.	Strong evidence for Linear over Null. Λ = 23256374216. Strong evidence for Linear over MIT. Λ = 283866611833.	Evidence for Linear Stronger.

2.2. III. Correlations. In total, 44 correlations were performed. The results will first be reported without controlling for the number of tests, then after controlling for the number with a Bonferroni correction. For the Bonferroni, the .05 p value is replaced with a new p-value which is calculated by dividing the original alpha-value (α-original = .05) by the number of comparisons (44): (α-altered = .05/44) = .001. There appeared to be no consistent correlations between the measures of physiological reactivity and subjective effort or fatigue or task performance. Separate correlations were conducted within each demand condition. In the low demand listening task, subjective effort was negatively correlated with task performance (r = -.40, n = 45, p = .003), and positively correlated with task reaction time (r = .26, n = 45, p = .04). This suggests that the more subjective effort invested the poorer and less efficient the performance. However, due to the very little variation in the low demand condition with regard to task performance (75% of participants scored 100%); this data is likely driven by a very small number of participants. There were no significant correlations between any measures in the moderately demanding listening task. In the highly demanding condition, RSA positively correlated with subjective effort (r = .27, n = 45, p = .04), the lower the RSA (PNS withdrawal) the lower the subjective effort. In the impossible listening task, RSA was also positively correlated with subjective effort (r = .27, n = 45, p = .04), and task performance (r = .33, n = 45, p = .01), indicating the lower the RSA (PNS withdrawal), the lower the subjective effort and the poorer the listening performance. RSA was negatively correlated with reaction time (r = -.29, n = 45, p = .03), indicating the lower the RSA (PNS withdrawal) the slower the reaction time. It is of note that this measure of SNS activity (PEP), although indicative of effort-related myocardial activity in response to listening demand, was not significantly correlated with any subjective or performance measures. After controlling for the number of correlations with a Bonferroni correction, none of the p-values reached statistical significance; no significant correlations were found.

2.3. Discussion

This second experiment aimed to investigate the limiting effect of the possibility to understand speech on the proportional relationship between listening effort and listening demand. The experiment intended to build on the findings from experiment 1, which shaped the design of this study in order to amend the limitations discovered. MIT predicts that although effort should increase as a function of task demand, one should never invest more effort than is minimally required for task success, using more effort necessary would be a waste of fundamental resources. Considering this, MIT states that one should not invest any effort in an impossible task, as success is unobtainable, any investment of resources would constitute waste. Using this framework, this experiment featured a listening demand manipulation over four levels, three possible tasks and one impossible. Listening effort was again quantified as ANS activation, reflected in parasympathetic withdrawal and sympathetic activation. Finally, the study aimed at understanding if any changes in ANS activation related to subjective effort, fatigue and task performance. Therefore, it was hypothesised that ANS activation (reflected in PNS withdrawal and SNS dominance) would increase as a function of listening demand while success was possible, and would show no response when success was unachievable. Subjective ratings of effort and fatigue would increase with possible demand, and show no response in impossible tasks. Furthermore, performance and response latency should decrease over all four levels.

2.3. I. Physiological Findings.

2.3. I. a. Parasympathetic reactivity. The planned contrast modelling an exponential decay with disengagement in the impossible listening task was not significant for RSA activity, indicating that PNS activity did not decrease in response to possible listening demand. Interestingly the descriptive statistics showed that the mean RSA scores for each condition displayed a reverse pattern to the initial prediction, with the highest level of PNS withdrawal occurring in the low demand and impossible tasks. To test MIT's prediction that the possibility of success limits the relationship between task demand and effort, the researcher compared the likelihood that the data occurred under MIT's model to a linear model that only considered task demand as a predictor of effort. The weak evidence found in favour of the MIT hypothesis for the RSA data was likely driven by the similar RSA values the low and impossible listening tasks, which suggests similar PNS reactivity in these two tasks. This data appears to support the hypothesis of low effort (PNS withdrawal) in both easy and impossible listening tasks. However, the data does not entirely support the hypothesis, as it was predicted that further PNS withdrawal would occur as listening demand increased. When comparing the MIT hypothesis to the null hypothesis of no effect, moderate evidence was found in favour of the null hypothesis, which further refutes the MIT hypothesis for PNS activity. However, fluctuations in breathing rate and depth could have affected the RSA data; slower breathing during the easy and impossible tasks due to minimal effort or relaxation could cause more variability in heart rate independently of PNS activity. Since the researcher did not control for respiration this is just an assumption.

2.3. I. b. Sympathetic reactivity. The planned contrast modelling an exponential increase and disengagement in the impossible listening task was significant for PEP-q reactivity, indicating that SNS activity increased exponentially in the possible listening tasks as a function of demand but did not change from baseline in the impossible task. This finding supports the predictions of MIT, that effort (quantified as SNS activity) increases as a function of task demand in possible tasks and no effort occurs in impossible tasks in order to avoid the waste of resources. This finding is in line with much of the research within the field of mental effort (for examples, Gendolla & Richter, 2006; Richter et al., 2008). Furthermore, it can provide support for the hypothesis that SNS is a valid indicator of effort in listening tasks as it responds reliably to both task demand and the limiting possibility of success. One can make this inference if listening demand is assumed to have an impact on effort and that the SNS activation constitutes this effort, but if this is assumed, the findings cannot also provide support for MIT's hypothesis that task demand influences effort, because this assumption has already been made. However, if the perspective that SNS activation constitutes effort is adopted (as defined in Wright's active coping hypothesis), then the conclusion can be drawn that listening effort occurs as a function of listening demand in possible tasks and does not occur in impossible tasks. This perspective provides evidence for MIT and facilitates the drawing of conclusions about the determinants of listening effort.

The pattern of SNS activation and no evidence for PNS withdrawal does not support this hypothesis but has been referred to in other models of ANS activation. In Berntson's Autonomic Space, this pattern alongside increased heart rate constitutes uncoupled sympathetic activation (Berntson et al., 1991). The likelihood ratio calculated based on the PEP data provided weak evidence in favour of MIT's model over a model that did not include the possibility of success as a limiting factor over the demand-effort relationship. Indicating that impossible tasks are more likely to induce disengagement than an exponential increase in SNS-driven effort, providing support for the energy conservation principle. However, the likelihood ratio test also provided weak evidence in favour of the null hypothesis over the MIT model. If an impossible listening demand situation does incur a withdrawal effect then this may help us to understand the issues that individuals with hearing impairment experience. People with hearing loss often report withdrawing from social events and experiencing isolation due to the demand that the environment places on their hearing (Hétu et al., 1988; Mick et al., 2014); this physiological data might provide extra evidence to support these claims. In addition, it would provide valuable information for hearing aid calibration to reduce demand or to encourage the considering of subjective and objective listening effort in standard audiological assessments.

2.3. I. c. Cardiac reactivity. Unlike the first study on listening demand within this thesis, SBP did not change as a function of listening demand. This finding is contradictory to many studies in the field that used this measure effort-related research (Gendolla & Richter, 2006b; Silvia et al., 2010). One might consider the PEP and SBP findings to contradict one another, since historically SBP was used an indicator of beta-adrenergic SNS activity. However, as discussed in the previous experiment, factors outside of SNS beta-adrenergic control such as peripheral resistance systematically influence SBP. Therefore, it is a less reliable measure of myocardial contractility than PEP.

The researcher collected HR data for the primary goal of ensuring that changes in PEP could represent SNS activity independently of the effects of preload or afterload. HR increased significantly as a function of listening demand, while success remained possible. The increase in HR enabled us to rule out any confounding effects on PEP; only a decrease in HR would permit increased ventricular filling time and shorten PEP independently of SNS activity. Studies on effort investment commonly observe increases in HR as a function of demand and often interpret such changes as reflecting SNS activation (Carroll, Rick Turner, & Hellawell, 1986; Richter et al., 2008; Sosnowski, Bala, & Rynkiewicz, 2010; Wright et al., 1986). However, this interpretation should be made with caution due to the difficulty in disentangling the SNS and PNS influence on heart rate. Increases in HR can be mediated by either increases in SNS activity or decreases in PNS activity, thus it is not possible to say which branch was most influential in increasing HR (Levick, 2003). Therefore, HR is not a good indicator of effort-driven SNS (or even PNS) reactivity in this study.

2.3. II. Subjective measures and listening performance. The planned contrasts indicated that self-reported fatigue did not respond according to MIT's model in the four listening demand conditions; this may be due to the type of task that the participants completed. A short laboratory-based listening task may not suffice to induce feelings of fatigue, especially not in a comparable sense to fatigue experienced by hearing impaired individuals. Furthermore, it is possible that the participants rated their fatigue to be greater towards the end of the full experiment; the data would not reflect this due to the randomisation of the task conditions. This explanation could be possible since the questionnaire addressed current feelings of fatigue, and not specifically listening task induced fatigue. The questionnaire was designed this way to reduce bias in the participants' responses, who might contemplate rating their fatigue more highly depending on their perception of the intended task difficulty, instead of their true state. Although this finding contrasts with other studies on fatigue in the hearing-impaired population (e.g. Kramer, Kapteyn, & Houtgast, 2006), it would be unreasonable to compare these findings to the reports of a clinical sample. A laboratory-based task is not able to induce the sustained daily effort and the potential resultant fatigue, nor is it possible to replicate accurately the demand experienced by hearing-impaired individuals.

However, it is noteworthy that a linear contrast was significant, indicating that subjective fatigue increased as a function of task demand even when the task was impossible. This finding was supported by the likelihood ratio tests, which provided weak evidence in favour of the linear model over the MIT model. This finding could be due to feelings of frustration with the impossible tasks leading the participants to feel the need to give up and 'worn out' by the task.

The planned contrast for self-reported effort was also significant highlighting that listening demand induced greater subjective effort while the task was possible and disengagement when the task became impossible. However, the likelihood ratio tests provided an alternative insight, indicating strong evidence in favour of the linear model over MIT, and strong evidence for the linear hypothesis over the null. Highlighting the discrepancy between subjective, objective and physiological data, both subjective effort and fatigue appear more affected by task demand and not as limited by the possibility of success.

2.3. III. Summary. In conclusion, evidence was found for effort-driven SNS activation as a function of listening demand while success was possible, in line with Wright's integrative active coping hypothesis (Wright, 1996). However, the hypothesis that SNS activation was accompanied by PNS withdrawal was not supported, evidencing an uncoupled mode of ANS activation during effortful listening (Berntson et al., 1991). However, it is possible that PEP is a much more sensitive measure of beta-adrenergic sympathetic activity on the heart than RSA is of parasympathetic influence. Any changes in PEP can be attributed to increased cardiac contractility caused by beta-adrenergic activity, because HR and DBP indicated no loading effects that could have shortened the length of PEP without sympathetic influence. However, a similar assurance cannot be made about RSA. RSA is parasympathetically mediated by the vagus nerve, but is highly influenced by respiration frequency and depth (Grossman, 2004). Because respiratory parameters were not controlled for in this study, it is possible that a pure measure of parasympathetic activation was not captured. Therefore, it is possible that effects were observed only for PEP due to reduced sensitivity of RSA as a measure of PNS activation. Furthermore, subjective measures of effort appear to be less limited by the possibility of success than physiologically quantified effort.

3. Phase Two: Experiments on Reward

The second phase of experiments investigated myocardial autonomic responses during conditions of unclear listening demand. A listening task with an unclear demand level is a task wherein the demand remains fixed, but the performer has no information about the required performance standard. As previously discussed, MIT proposes that to use resources efficiently, effort occurs as a function of demand while success is possible and effort is justified (Brehm, 1989). However, how should an individual ensure they invest effort efficiently if they cannot adjust it in line with task demand? According to Brehm's theory, to avoid the unnecessary use of limited mental resources, individuals use alternative information about the task or given activity to adjust their effort investment accordingly in unclear tasks. The importance of success (or potential motivation) is the upper limit that delineates the maximum amount of resources justified for successful goal attainment. When the demand of a task is unclear, effort occurs as a function of the importance of success; this ensures that one never invests more effort than justified for goal attainment.

Most of the empirical evidence for MIT's prediction about effort investment in tasks with unclear demand relied on Wright's (1996) integrative definition of effort investment in active coping, as beta-adrenergic myocardial sympathetic activity. Using measures of myocardial sympathetic activity (PEP and SBP) researchers have found that effort increases as a function of monetary reward in cognitive tasks with a fixed but unclear demand level (Gendolla & Richter, 2006b; Richter & Gendolla, 2007, 2009b). These studies manipulated the importance of success using financial incentives. Other studies demonstrate that individualistic factors influence the magnitude of success importance, thus affecting the amount of (SNS driven) effort allocated to a task. For example, personality traits like self-focused attention (Silvia et al., 2010), perseverance (Silvia et al., 2013), and the need for closure (Richter et al., 2012) lead to increases in the upper limit of motivation for a given task. Using Wright's integrative framework, one study found that mood influences potential motivation and thus effort investment through the estimated instrumentality of success (Richter & Gendolla, 2009a). Additional research on the impact of reward during effort investment finds that dysphoric individuals display reduced cardiovascular reactivity during cognitive tasks with unclear performance standards due to a motivational deficit when anticipating task rewards (Brinkmann & Franzen, 2013; Brinkmann et al., 2014).

Yet, as in most of the empirical research on the predictions of MIT, the focus on beta-adrenergic SNS activity as the exclusive definition of effort provides a limited perspective of effort as a function of success importance in tasks with no clear performance standard. The reduction of the physiology of mental effort to exclusively sympathetic reactivity is contradictory to putative perspectives in the physiology of physical effort. At low intensity physical activity, the withdrawal of inhibiting PNS activity mediates increases in effort related cardiac activity (Robinson et al., 1966). Cardiac reactivity driven by increases in sympathetic activity are required only during high intensity physical tasks requiring increased effort (White & Raven, 2014). As suggested by other researchers in the field, the exclusive use of SNS cardiovascular measures in the MIT research on mental effort and reward are potentially limited to investigating cardiovascular reactivity required at high intensity only (Richter, Gendolla, & Wright, 2016). Furthermore, many other psychophysiological theories on the regulation of cardiac activity acknowledge the roles of both branches of the ANS (for example, Berntson's modes of autonomic control (1991) and Porges' polyvagal theory (2007)). A sole focus on SNS activation, and limited research on PNS reactivity, obstructs a holistic understanding of the link between the ANS activity and the predictions of MIT regarding the effort-reward relationship during unclear task demand.

Studies on listening effort that did not use MIT or Wright's integrative perspective have used both PNS and SNS measures simultaneously during effortful listening (Mackersie & Calderon-Moultrie, 2016; Mackersie et al., 2015; Seeman & Sims, 2015). However, these studies often assess PNS and SNS activity at different organs, and given that, the outflow of these branches to organs is not uniform throughout the body (Esler, Hasking, Willett, Leonard, & Jennings, 1985), it prevents the drawing of conclusions about specific autonomic balance during effortful listening. Furthermore, these studies focus on the assumption that effort is a direct function of task demand, ignoring other motivational factors that may influence effort investment. Over recent years, the research on listening effort has begun to acknowledge the role of motivation. Hornsby and Kipp (2016) suggested that daily life for individuals with hearing loss is an exemplar of a high-effort and low-reward situation. They considered that the need to maintain increased levels of listening effort over extended time as well as trouble with communication, results in a minimal reward for the effort that is required. They related this experience to the manifestation of hearing fatigue that occurs in response to a loss of motivation to continue with a task (Hockey, 2011; Hornsby & Kipp, 2016). The recent consensus article by Pichora-Fuller and colleagues (2016), wherein key researchers devised the Framework for Effortful Listening (FUEL), provided a progressive perspective that included both auditory, cognitive, motivational and physiological insights. The contributing researchers emphasised that when and how much effort is invested during listening depends on the individuals motivation to achieve success, and attain rewards of personal or social value (Pichora-Fuller et al., 2016). Despite a clear shift in census in the listening effort field, only a couple of studies have directly looked at the effect of reward on effortful listening (Koelewijn et al., 2018; Richter, 2016b). Koelewijn and colleagues found that the peak pupil dilation showed a significantly larger response when the reward for successful completion of a listening task was high (€5) compared to low (€0.20), when the task was both easy and difficult

(Koelewijn et al., 2018). Another study showed that pupil dilation responds to reward value (valuable vs. non valuable) in an auditory task (Bijleveld, Custers, & Aarts, 2009). The results provided evidence of SNS-related listening effort in response to increased reward incentive, but no study thus far considered the effect of success importance on both branches of the ANS.

The following two studies on the impact of reward on listening effort will seek to provide empirical evidence for a broader take on the determinants of listening effort based on key psychophysiological theories and perspectives. Previous research within the first stage of this thesis demonstrated that myocardial sympathetic activity increases as a function of listening demand, providing support for the central prediction of MIT. The studies within this second phase will build upon this core research by investigating the impact of reward on listening effort in comprehension tasks without a clear performance standard. These studies will maintain the inclusive and theory-driven approach applied in previous studies to understand the autonomic determinants of effortful listening using both measures of PNS and SNS activity.

3.1. Experiment 3: The relationship between reward and effort-driven cardiovascular responses

The two previous experiments focused solely on listening demand and the resulting effect on effort-driven cardiovascular responses. However, MIT's 'third' prediction suggests another important construct governs effort expenditure: reward. The importance of success is of significance when one cannot adjust effort based on task demand, due to lack of clarity. In this case, effort investment (quantified by myocardial SNS and PNS activity) should increase as a function of the importance of success (manipulated in this study by reward). Additionally, higher ratings of subjective effort and fatigue in response to reward should accompany the observed change in autonomic activity.

3.2. Method

3.2. I. Participants and Design. A sample of 42[5] adults, 24 female and 18 male (mean age of 27.76 years), with normal hearing participated for a potential 12-GBP in Amazon vouchers. The same pre-screening session as in Experiments 1 and 2 confirmed the participants' hearing threshold; those identifying five or more tones were eligible to take part. Emails, social media, and advertisement posters displayed at Liverpool John Moores University recruited the sample. All participants completed four reward conditions of a speech recognition task: no reward, low reward, moderate reward or high reward.

3.2. II. Procedure. As in both experiments in Phase One, Inquisit by Millisecond Software (Seattle, WA) controlled the presentation of the experimental stimuli and collected participant's responses. Each participant took part individually and gave informed consent, after which the researcher measured the participant's height and weight. The same physiological measurements were employed in this experiment as were used in Phase One. The indicators of SNS and PNS activity, PEP and RSA, were measured using ICG and ECG signals sampled at a rate of 1000Hz. The ICG and ECG signals were collected from four pairs of electrodes from a Cardioscreen 1000

[5] Sample size was determined using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) setting alpha error to 5%, beta error to 5% and f to 0.25.

attached to the left and right side of the participant's chest and neck. A Dinamap Carescape V100 monitor blood pressure cuff attached to the participant's non-dominant arm measured SBP and DBP values at two-minute intervals using the oscillometric method. HR and DBP values controlled for changes in cardiac preload and afterload that could influence PEP.

After hearing a verbal explanation of the experimental structure, the participant provided their age and gender. The participant completed the 9-item fatigue questionnaire that was also employed in Experiment 2 (see appendix 3). For each item, the participant selected a word from two comparative adjectives displayed on the screen that best described their current state. Then they completed a 6-minute baseline period in which they viewed a clip from the documentary 'Kingdom of Plants'. During this time, the researcher recorded cardiovascular activity using the CardioScreen, which sampled the ECG and ICG signals. Sixty seconds after the onset of the baseline, the researcher recorded SBP and DBP values at 2-minute intervals. The participant then completed the first of four conditions of a speech in pure white noise task, with an unclear demand level (SiWN-U). Each of the four task conditions consisted of 10 trials; in each trial, the participant listened via headphones to a 32-second short story spoken by a female voice, in the presence of white noise. The speech was presented at 50dB. After hearing the audio, the participant answered a multiple-choice question (with three possible answers) about the story within a 5-second time limit. With the aim of creating a task with an unclear difficulty level, the white noise presented with the trials in each condition remained fixed but varied from very quiet (-36dB) to very loud (-0dB). The order of the trials was randomised. At the beginning of each condition, the participant was informed that the computer would select a target score ranging from five to ten correct responses. If the participant could correctly answer enough of the multiple-choice questions to achieve this target score, they would earn a reward. The reward value was announced before the condition: either a £0 Amazon Voucher, a £2 Amazon Voucher, a £4 Amazon Voucher or a £6 Amazon Voucher. In this task, the difficulty level remained constant in all four conditions, but it remained unclear to the participant due to the varying level of white noise and the ambiguity of the target score. During the task the researcher recorded cardiovascular activity using ICG and ECG signals collected from the CardioScreen, and SPB and DBP values at 2-minute intervals.

After completing the task, the participant answered two questionnaires. They completed the 9-item fatigue questionnaire again, as described at the beginning of this procedure section. The participant then completed a modified version of the NASA Load Index (NASA-TLX) (Hart & Staveland, 1988), as in both experiments in Phase One, the two items representing mental demand and effort were extracted and used. After the participant completed all four conditions, the researcher debriefed and remunerated them.

3.2. III. Data Analysis. PEP quantified myocardial SNS activity in the same manner as in the experiments in Phase One. The researcher scored PEP values (in milliseconds, computed as the interval between the Q-point on the ECG and the B-point on the ICG) for each 60-second ensemble average. The researcher computed change scores between task and baseline values of PEP to represent the change in SNS activity.

The quantification of myocardial PNS activity followed the same procedure as used in both previous experiments using offline R-peak detection (in BlueBox, Richter, 2010) and Kubios Analysis software that calculated HF-HRV using the FFT technique (Tarvainen et al., 2014). The mean HR was also collected from the Kubios analysis software. The change score between task and baseline values of HF-HRV determined the change in PNS activity. The researcher calculated the arithmetic mean of SBP and DBP values recorded during the baseline and task periods, the change scores between task and respective baseline values for HR, SBP and DBP were calculated. HR and DBP were collected for controlling the influence of cardiac preload and afterload on PEP.

Change between task and baseline scores on the fatigue questionnaire (after appropriate reverse scoring) indicated subjective fatigue. Mean response time in seconds during each reward condition of the listening task quantified objective fatigue. The sum of responses given on the two NASA-TLX items quantified subjective effort and the total number of correct responses in each condition determined task performance.

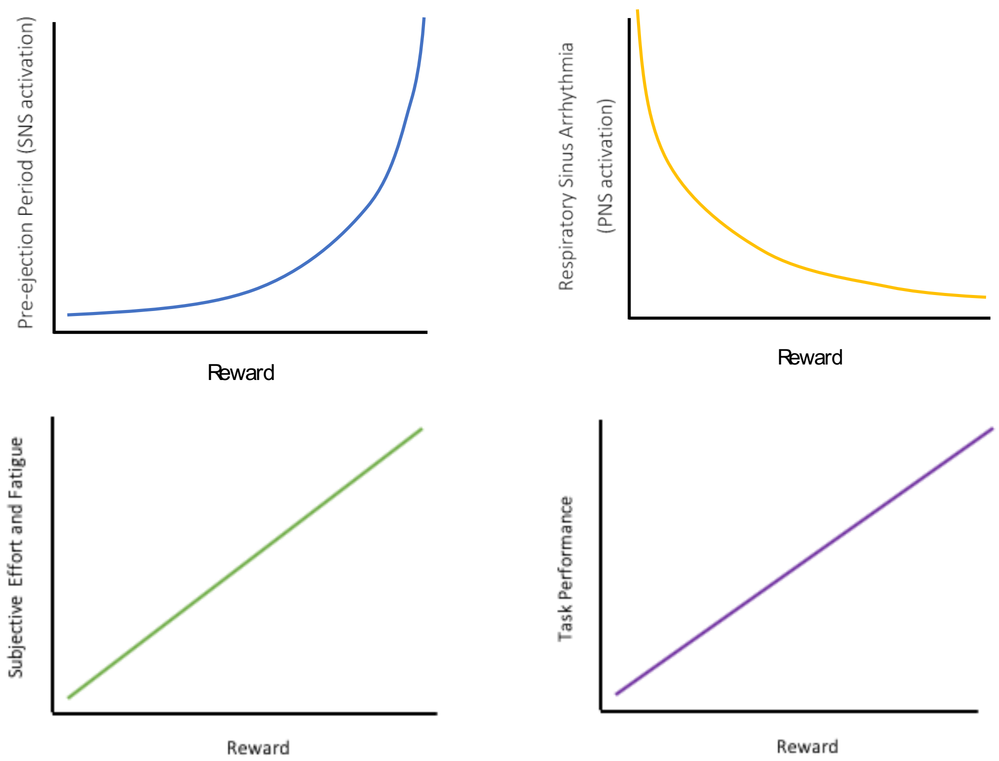

Figure 15.

A figure illustrating the hypothesised effects. SNS activation is hypothesises to increased exponentially as a function of reward, while PNS activation should decrease exponentially. Subjective measures and task performance are expected to increase as a function of reward.

Planned contrasts tested the hypothesis about the impact of reward on myocardial autonomic activity and subjective ratings of effort and fatigue. The four reward conditions were assigned to the following contrast weights: no reward 8.5, low reward 0.5, moderate reward -3.5, high reward -5.5; which models an exponential decay to test the prediction that PNS activity decreases with increased reward incentive. Contrast weights which model an exponential increase (-5.5, -3.5, 0.5, 8.5) were used to test the prediction that SNS activity increases as a function of reward incentive. Linear contrasts tested the predictions that subjective effort and fatigue would increase as a function of reward incentive, and to test the prediction task performance and response times would improve as a function of incentive.

3.3. Results

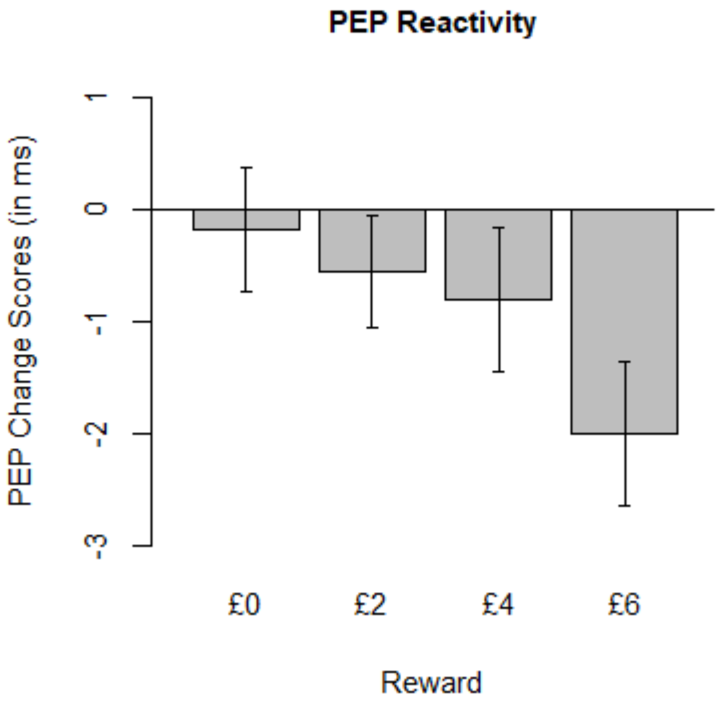

Figure 16.

Mean PEP Change Scores for Each Reward Condition. Error Bars Represent Standard Errors. PEP Indicates Pre-Ejection Period.

3.4. I. Planned Contrasts.

3.4. I. a. Cardiovascular Response. Planned contrasts revealed no significant effect of reward on RSA, $t(41) = 0.02$, $p = .44$. Indicating that PNS reactivity, operationalised as RSA, did not significantly decrease in response to reward incentive. Nor was there a significant effect of reward on SBP, $t(41) = 0.92$, $p = .18$. However, PEP reactivity was found to significantly decrease in response to increased reward, $t(41) = 2.48$, $p = .009$, see Figure 16. Both the analysis of HR and DBP highlighted a significant relationship between these two measures and increased reward, $t(41) = 1.89$, $p = .03$ and $t(41) = 2.75$, $p = .004$ respectively. Since these results indicate increases in both

HR and DBP, any changes in PEP can be attributed to SNS induced myocardial contractility and not increased preload or afterload. The exponential decrease in PEP indicates that SNS activity increased as a function of reward incentive. The contrast analysis revealed no significant increase in total ANS activity in response to reward incentive $t(41) = 1.30$, $p = .09$. The mean change scores and standard errors of all cardiovascular measures can be found in Table 11.

Table 11.

Change Score Means and Standard Errors (in Parentheses) of Cardiovascular Responses During the Four Reward Conditions of the SiWN-U.

	No Reward	Low Reward	Moderate Reward	High Reward
HR	2.01 (0.72)	2.64 (0.56)	2.56 (0.53)	3.15 (0.69)
DBP	-0.05 (0.47)	0.57 (0.55)	1.44 (0.56)	1.73 (0.46)
SBP	-0.27 (0.82)	1.10 (0.80)	1.85 (0.65)	0.97 (0.90)
RSA	-2.13 (1.54)	-1.78 (1.33)	-2.69 (1.71)	-2.21 (1.84)
PEP	-0.18 (0.56)	-0.55 (0.51)	-0.81 (0.64)	-2.00 (0.64)
ANS	0.28 (0.22)	0.34 (0.19)	0.41 (0.23)	0.66 (0.21)

3.4. I. b. Subjective Measures and Performance. No significant increases in self-reported fatigue were found in response to reward incentive, $t(41) = 1.42$, $p = .08$, nor were there significant decreases in task performance, $t(41) = 1.18$, $p = .12$. Response time however, became significantly longer as a function of reward, $t(41) = 3.03$, $p = .002$. And, a significant increase in self-reported effort was found as a function of increased reward $t(41) = 4.18$, $p = .001$. This indicates that individuals considered themselves to be investing more effort when the value of the reward incentive was higher. However, interestingly this is not reflected in their task performance. Descriptive statistics for all subjective and performance data can be found in Table 12.

Table 12.

Means and Standard Errors (in Parentheses) of Self-Reports and Task Performance in the Four Reward Conditions of the SiWN-U. Ten trials were presented in each condition, therefore task performance could reach a maximum of 10.

	No Reward	Low Reward	Moderate Reward	High Reward
Subjective Effort	8.52 (0.36)	9.19 (0.35)	9.19 (0.39)	9.93 (0.38)
Subjective Fatigue	1.45 (0.48)	1.83 (0.55)	1.76 (0.58)	2.29 (0.52)
Task Performance	7.81 (0.19)	8.07 (0.17)	8.19 (0.23)	7.45 (0.23)
Response Latency	2.77 (0.10)	2.68 (0.09)	2.68 (0.10)	3.06 (0.11)

3.4. II. Correlations. In total, 44 correlations were performed. The results will first be reported without controlling for the number of tests, then after controlling for the number with a Bonferroni correction. For the Bonferroni, the .05 p value is replaced with a new p-value which is calculated by dividing the original alpha-value (α-original = .05) by the number of comparisons (44): (α-altered = .05/44) = .001. Correlations were conducted within each reward condition to investigate the potential relationship between the physiological indicators of effort and subjective effort and fatigue, and task performance. The aim of this analysis was to understand the emergence of subjective fatigue and decrements in listening performance, and whether these factors are more likely related to effort-driven physiological reactivity or subjective effort. No consistent correlations were found between the physiological measures and subjective ratings or performance scores. The only significant correlation emerged in the no reward listening task, where PEP correlated positively with subjective fatigue, (r = -.37, n = 40, p = .009), indicating that when there was no reward (or low success importance) reductions in PEP indicative of effort were related to higher subjective fatigue. Largely consistent correlations were found between subjective effort and subjective fatigue in all reward conditions bar no reward. Subjective effort was positively correlated with subjective fatigue in the low reward condition (r = .34, n = 40, p = .01). In the moderate reward and high reward conditions positive correlations were found between subjective effort and fatigue (r = .43, n = 40, p = .003 and r = .43, n = 40, p = .003 respectively); please see figure 17 for a scatter plot of these two correlations. These findings indicate a relationship between increased subjective effort and increased fatigue that becomes stronger as success importance increases. After controlling for the number of tests performed using Bonferroni, none of the correlations reached statistical significance.

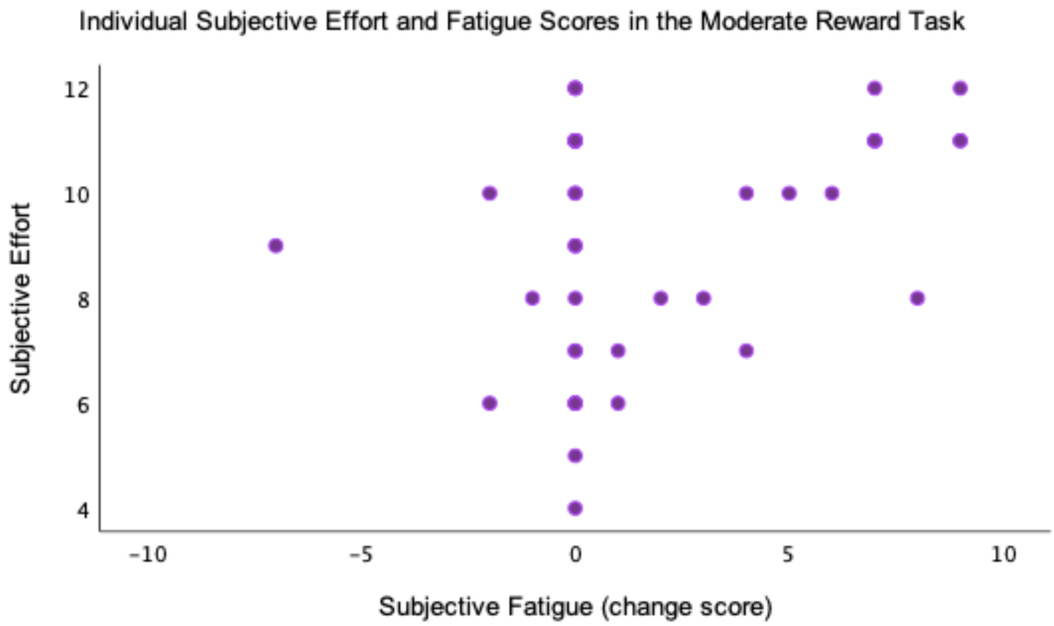

Figure 17.

A scatterplot of the individual subjective effort and fatigue scores within the listening task with a moderate reward level.

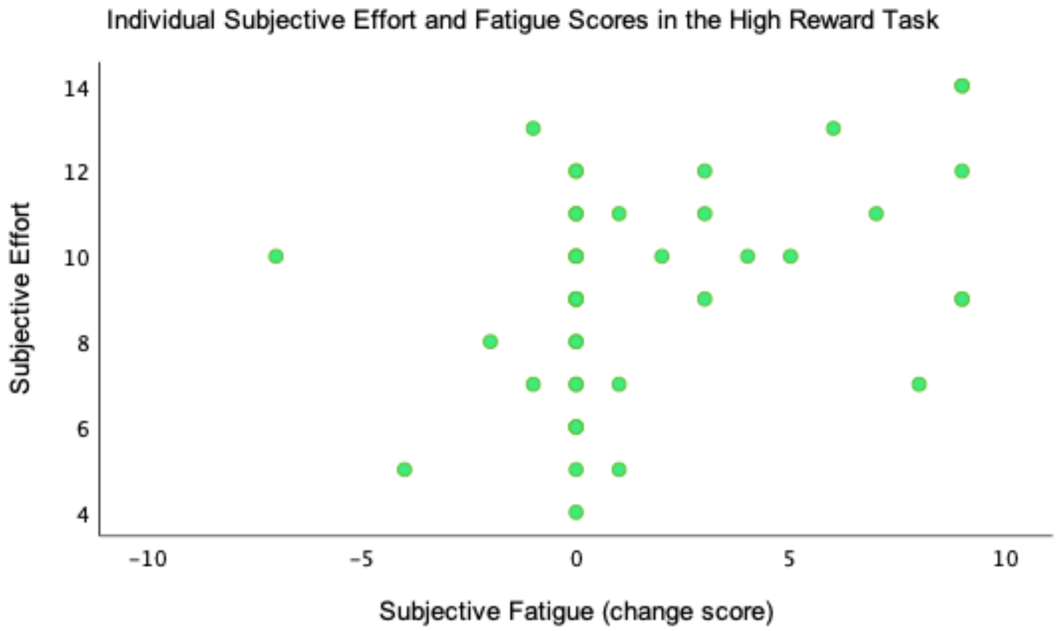

Figure 18.

A scatterplot of the individual subjective effort and fatigue scores within the listening task with a high reward level.

3.5. Discussion

This study aimed to provide a broader psychological perspective on effortful listening. Based on MIT (Brehm, 1989), it was predicted that listening effort (indexed by cardiovascular reactivity, reflected in PNS withdrawal and SNS activation) would increase as a function of incentive value in listening tasks with a fixed but, unclear performance standard. Similar increases in subjective effort and fatigue were also predicted, and these self-reported findings were expected to relate to any discovered changes in autonomic reactivity.

3.5. I. Reward and Physiological Reactivity. The planned contrast analyses revealed that increases in reward did not have a significant effect on RSA; suggesting that an exponential decay in PNS activity did not occur as a function of reward in listening tasks with no clear performance standard. However, interpreting changes in

RSA in this study as PNS reactivity may be naïve. There are confounding variables that influence the magnitude of RSA independently of PNS influence, such as posture, respiratory frequency and breathing depth (Grossman, 2004; Grossman & Taylor, 2007; Houtveen, Groot, & De Geus, 2005). The participants were stationary throughout this experiment, so intervening effects of rapid increases or decreases in breathing or changes in body posture were unlikely to occur in this situation. Nonetheless, these variables are still important to consider when interpreting the data as evidence for listening effort-related PNS reactivity.

Conversely, incentive had a significant effect on measures of PEP, suggesting that as reward for task success increased there was an exponential increase in SNS activity. Much of the research conducted on MIT's prediction about effort investment in unclear tasks has relied on measures of SNS activity to quantify effort (for examples see, Richter & Gendolla, 2007, 2009b). This study thus adds to the growing body of evidence for effort investment as a function of reward during tasks with unclear demand. Importantly, this research was the first to demonstrate evidence for this hypothesis in a listening task, underlining the role of motivational factors in effortful listening beyond task demand. The finding supports the rising evidence base in the listening effort field that seeks to highlight the importance of an inclusive theory-based perspective that encompasses both motivation science and psychophysiology. Yet, the planned contrast was not significant for the effect of reward on SBP, which has been employed as an efficacious measure of effort-driven SNS activity in previous research on tasks with a clear difficulty level (for examples see, Gendolla & Krüsken, 2002; Light, 1981) and unclear difficulty level (Richter & Gendolla, 2007). Nevertheless, drawing on the SBP change scores in this experiment, increases in SBP occurred in all rewarded listening tasks compared to the task with no incentive. Additionally, SBP is not the purest indicator of SNS activity, as it is influenced not only by myocardial contractility but also total peripheral resistance, which can be mediated by SNS and PNS reactivity (Brinkmann & Franzen, 2013; Levick, 2003; Silvia et al., 2010). Since PEP is the non-invasive 'gold standard' for the measurement of beta-adrenergic myocardial activity, reward was concluded to have a significant effect on listening effort.

Linear contrasts for the effect of reward on HR and DBP were significant, indicating that both these parameters increased as a function of reward; confirming that beta-adrenergic activity shortened PEP independently of cardiac loading effects. Most of the current research using Wright's integrative perspective have not found consistent evidence for the role of HR or DBP in effort investment (e.g. Richter & Gendolla, 2006). Although increases in HR and DBP indicate some form of cardiac reactivity related to increased reward, like SBP, both these measures are influenced by both SNS and PNS reactivity. Total peripheral resistance has an even larger effect on DBP than SBP and thus any influence of myocardial contractility on DBP is likely overshadowed, and HR can only be interpreted as SNS activity if PNS influence is entirely stable (Richter, 2010). Therefore, reliance on these measures would thus limit understanding of the autonomic correlates of effortful listening as a function of success importance.

3.5. II. Reward and Subjective Effort and Fatigue and Performance. Contrast analyses suggested that although individuals rated the listening task to be more effortful as a function of reward, they did not experience consequential hearing fatigue. Considering this, the fatigue change score from baseline was higher in all rewarded conditions compared to no reward. Yet, the lack of a significant effect of reward on fatigue could be explained by research that suggests the experiencing of fatigue can be off-set by the presence of reward (J. Hopstaken, 2016; Hornsby & Kipp, 2016). These researchers propose that incentive alters task motivation, leading to increased effort without fatigue. This explanation might hold in short-term lab-based listening tasks, but for hearing impaired individuals in everyday life the general consensus is that it is the sustained effort investment in daily life communication that gives rise to hearing fatigue (Pichora-Fuller et al., 2016). Reward had no significant effect on listening accuracy as performance was more likely driven by trial-by-trial demand than task demand. In each task, there were trials of differing difficulty and all tasks consisted of the same number of easy, moderate, difficult and impossible trials, thus it is unsurprising that performance remained stable throughout the conditions. It is of note that performance remained at around 78% in the no reward condition, suggesting that individuals were still motivated to complete the task even though, according to MIT, their level of potential motivation would have been very low at this point. There are a number of reasons to explain this effect including the fact that the task was objectively easy; participants may have still been able to perform well while utilising little-to-no effort. Furthermore, participants are instructed to perform as accurately as possible, which may have increased their potential motivation independent of the reward manipulation. As well as this, participants are paid for taking part in the study which provides an additional external motivator. There was a significant effect of reward on response latency; however, the difference was only by a matter of milliseconds. This may indicate that participants were more cautious in selecting the correct response when a higher reward was at stake.

3.5. III. Relationship between Physiological Effort, Subjective Reports and Listening Performance. A second aim of this thesis was to understand the emergence of hearing fatigue and subjective listening effort in the hearing-impaired population, as understanding their origins could improve well-being for those with hearing loss. The lack of consistent correlation between the physiological measures and self-reports in this study suggest that these parameters are unrelated. For example, variations in listening effort-driven SNS activity do not likely relate to variations in self-reports; those who invested more or less listening effort as a function of reward did not experience accompanying subjective effort or hearing fatigue. This finding is not uncommon in the listening effort literature (McGarrigle et al., 2014). It is possible that physiological and mental effort, or indeed fatigue, manifest separately and on different timescales. Lab-based listening studies may be unable to elicit the level of effort experienced by hearing impaired individuals in the real world.

However, in all rewarded conditions (bar no reward), positive correlations were found between subjective effort and subjective fatigue ratings, with the strongest correlations in the two highest reward conditions. These correlations provide insight into the effect of reward on the relationship between listening effort and hearing fatigue: the higher the subjective effort, the higher the subjective fatigue, especially in the presence of high reward. It might be useful for clinical application to consider incorporating measurements of subjective effort in audiological assessments as it could be related to the manifestation of hearing fatigue or vice versa.

This experiment provided evidence for increased SNS-related listening effort as a function of reward in unclear demand listening tasks, providing the first support for MIT's predictions in a listening task. These results highlight the importance of motivational factors in understanding effortful listening and thus, a broad perspective in the quantification of listening effort is essential.

4. Experiment 4: The relationship between reward and effort-driven cardiovascular responses.

Experiment 3 provided evidence for the significant impact of reward incentive on effort-driven sympathetic activity and subjective effort ratings. This fourth experiment aims to expand on these findings by demonstrating the strong effect that reward can have on effort in tasks with an unclear demand, in comparison to its impact on a task with a clear demand level. According to MIT, in a clearly easy task, effort is low regardless of the importance of success (or reward) because the task is easy. If one were to invest more effort than required for this task, it would be a waste of vital resources and oppose the energy conservation principle. Whereas, if the same task is presented in a way that the demand level is unclear to the individual, the importance of success (or reward) should govern the amount of effort to be invested (Brinkmann & Franzen, 2013; Richter, 2013; Wright, 2008). For example, imagine a challenge that involves picking up a small container to earn a reward. In one situation, the container is translucent, empty and clearly very light in weight. Regardless of the reward associated with lifting the container, only the small amount of energy required to lift it will be used. Conversely, imagine that the container is opaque, you cannot see the contents and you do not know how much it weighs. In this case, the amount of reward offered for picking up the container would change the amount of force used to lift it, if there is a significant reward at stake, say £100, one would use substantial force to guarantee gaining the reward, even if the container is empty.

4.1. Method

4.1. I. Participants and Design. A sample of 58[6] adults, 35 females and 23 males with a mean age of 24.40 years, with no impaired hearing and without pacemakers took part in this experiment. Emails, social media and posters displayed at Liverpool John Moores University recruited the participants. All participants took part individually and for remuneration in the form of a potential £10 GBP in Amazon Vouchers. The participants were systematically assigned to one of two groups: unclear or clear task demand, with an equal number of participants in each group. Within each group the participant competed two reward conditions of a low demand speech in pure white noise task (SiWN-Easy): low reward (£1) and high reward (£9), presented in a random order. In the clear demand group in both the low and high reward conditions, effort investment should be minimal, as the demand of the task, not the importance of success, governs effort. Whereas, in the unclear group, effort should be minimal in the low reward condition but elevated in the high reward condition, because when task demand is not clear, the importance of success governs effort.

4.1. II. Procedure. Inquisit by Millisecond Software (Seattle, WA) controlled the presentation of the experimental stimuli and collected participant's responses. The researcher measured the participant's height and weight and attached four pairs of electrodes from an impedance cardiograph (Medis Medizinische Messtechnik GmbH, Illmenau, Germany) to the left and right sides of the participant's neck and chest.

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[6] Sample size was determined using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) setting alpha error to 5%, beta error to 5% and f to 0.25.

The cardiograph sampled an ECG and ICG at a rate of 1000Hz; the resulting R-R interbeat interval series and dZ/dt signal allowed for the calculation of PEP and RSA, to quantify SNS and PNS activity respectively, and to calculate HR. A blood pressure cuff from a Dinamap Carescape V100 monitor fastened to the participant's upper left arm measured SBP and DBP using the oscillometric method at two-minute intervals.

The participant provided their age and gender and read on-screen instructions about the experimental tasks which differed slightly depending on their group assignment (clear demand vs. unclear demand). The participant then completed one of two listening tasks, either low reward (£1) or high reward (£9). At the beginning of the task block, the participant was informed of the potential reward value for successful task completion. Within each block, the participant completed a pre-test 9-item fatigue questionnaire, a 6-minute baseline, a 10-trial listening task, a post-test fatigue questionnaire and a post-test effort questionnaire. This experiment employed the same fatigue questionnaire used in previous experiments 2 and 3, wherein participant selected a word that best represented their current state from two comparative adjectives expressing either fatigue or alertness. The participant then watched a 6-minute video clip from the documentary 'Kingdom of Plants', during this baseline the researcher recorded ICG and ECG signals, and SBP and DBP values at 2-minute intervals after the first minute.

The participant then completed 10 randomised trials of the SiWN-Easy task, during which the researcher recorded ICG and ECG signals and SBP and DBP values at 2-minute intervals. In each trial, the computer played an audio clip lasting 32-seconds to the participant through headphones. The clip contained a short story spoken in English by a female voice alongside white noise. The speech was presented at 50dB. In all trials the white noise was presented at -18dB (in two trials), -24dB (in three trials), -30dB (in three trials), or -36dB (in two trials) quieter than the speech. In all trials the speech the could be heard clearly over the top of the white noise, but only one participant group was made aware of this fact (the clear demand group). The researcher had informed these participants that although the volume of the white noise would vary throughout the task, it would always be quiet enough to hear the speech clearly in all trials. Whereas, the participants in the unclear demand group received instructions that the volume of the white noise would range from very quiet, where it should be easy to hear the speech, to very loud, where it should be impossible to hear the speech.

The participants answered a comprehension question in a 5-second response window after each trial; the time limit was fully disclosed to participants in the clear demand group. Whereas the participants in the unclear demand group were informed that the response window would time-out in an undisclosed period. In the clear demand group, the participants were informed that answering nine comprehension questions correctly (out of 10) would earn them the reward voucher (£1 or £9). Whereas, those in the unclear demand group were told that the computer would select an undisclosed target score, which could range from one correct response to 10 correct responses. If the participant reached or exceeded this hidden target, they would earn the reward voucher (£1 or £9).

After completing the first SiWN-Easy task, the participant answered the 9-item fatigue questionnaire for a second time. The participant then answered two questions (on mental demand and effort) from the NASA Load Index (NASA-TLX) (Hart & Staveland, 1988), as in previous experiments. The participant then completed the remaining SiWN-Easy task, as detailed above; the task comprised a pre-test fatigue questionnaire, a 6-minute baseline, a 10-trial listening task, a post-test fatigue questionnaire and a post-test effort questionnaire. After completing both SiWN-Easy tasks (£1 reward and £9 reward), all participants were given their task scores and remunerated with Amazon Vouchers for attaining a 9/10 performance standard.

4.1. III. Data Analysis. PEP quantified myocardial SNS activity in the same manner as in the previous experiments. The researcher scored the PEP values (in milliseconds, computed as the interval between the Q-point on the ECG and the B-point on the ICG). Change scores between task and baseline values of PEP were computed and used to represent the change in SNS activity. Myocardial PNS activity was quantified via the same procedure as used in all previous experiments using offline R-peak detection (in BlueBox (Richter, 2009)) and Kubios Analysis software that calculated RSA using the FFT technique (Tarvainen et al., 2014). Mean HR was also collected from Kubios analysis software. The change score between task and baseline values of RSA determined the change in PNS activity. SBP and DBP values recording during the baselines and tasks were averaged to create mean values for each task and baseline period. The change scores between task and the respective baseline values for HR, SBP and DBP were calculated. HR and DBP were collected for controlling the influence of cardiac preload and afterload.

Mixed model planned contrasts tested the hypothesis on the impact of task demand clarity and reward on myocardial autonomic activity and subjective ratings of effort and fatigue. The four conditions were assigned to the following contrast weights: clear demand- low reward -1, clear demand- high reward -1, unclear demand- low reward -1, and unclear demand- high reward 3. These weights were used to model the predictions of MIT, that in a clearly easy task little-to-no effort should be expended whereas, in a task with an unclear demand effort should be invested as a function of reward. These contrast weights were also employed for the behavioural data, to test the exploratory prediction that when little-to-no effort is invested due to low success importance, or objectively easy demand; participants are more likely to make errors. This may be because the level of invested effort is reduced, and fewer resources are allocated to the task, increasing the likelihood of incorrect responses. Alternatively it could be due to attention; research shows that it is usually harder to maintain attention in unchallenging, uninteresting tasks than in cognitively demanding ones (Langner & Eickhoff, 2013; Kahneman, 1973). Due to the mixed design used in this study, the researcher followed the effect-size aggregation procedure outlined in Rosenthal & Rosnow (1985) to calculate the effect size to be used in the planned contrasts.

4.2. Results

4.2. I. Planned Contrasts.

4.2. I. a. Cardiovascular Response. The planned contrast for PEP reactivity was not significant $t(56) = 0.43$, $p = .33$, nor was the contrast for RSA $t(56) = 0.26$, $p = .40$, or SBP $t(56) = 0.61$, $p = .27$. The planned contrast for total autonomic nervous system activity was also not significant, $t(56) = 0.11$, $p = .46$. The planned contrasts for HR and DBP, to be used as controls in the quantification of PEP as sympathetic activity, were also not significant ($t(56) = 0.37$, $p = .36$, and $t(56) = 0.74$, $p = .23$ respectively). The planned contrasts tested the prediction that cardiovascular reactivity should be highest in the task where listening demand was unclear alongside the possibility of a high reward. In the remaining three conditions, there should be no reactivity. The contrast analysis did not find significant evidence for this pattern. The mean change scores and standard errors for all physiological parameters can be found in Table 13.

Table 13.

Change Score Means and Standard Errors (in parentheses) of Cardiovascular Responses During the Four Conditions of the SiWN-Easy.

	Clear Demand		Unclear Demand	
	Low Reward	High Reward	Low Reward	High Reward
HR	4.53 (0.67)	5.73 (0.77)	3.82 (0.68)	5.00 (0.77)
DBP	1.56 (0.63)	2.24 (0.71)	1.59 (0.63)	2.37 (0.71)
SBP	2.82 (0.81)	4.40 (0.76)	2.64 (0.81)	3.84 (0.76)
RSA	-1.22 (2.51)	-2.07 (2.18)	-2.13 (2.51)	-2.52 (2.18)
PEP	-2.01 (0.50)	-2.01 (0.64)	-1.13 (0.50)	-2.00 (0.64)
ANS	0.83 (0.25)	0.76 (0.22)	0.58 (0.25)	0.80 (0.22)

4.2. I. b. Subjective Measures and Performance. In addition, the planned contrast analysis revealed that listening condition had no significant effect on self-reported effort ($t(56) = 0.24$, $p = .40$) or self-reported fatigue ($t(56) = 0.08$, $p = .47$), or response latency ($t(56) = 1.51$, $p = .07$). However, the contrast analysis for performance and response latency were significant ($t(56) = 2.56$, $p = .008$ and $t(56) = 5.01$, $p < .001$). The mean and standard error for the self-reported and performance data can be found in Table 14.

Table 14.

Change Score Means and Standard Errors (in parentheses) of Self-Reports and Task Performance During the Four Conditions of the SiWN-Easy.

	Clear Demand		Unclear Demand	
	Low Reward	High Reward	Low Reward	High Reward
Subjective Effort	8.41 (0.54)	8.90 (0.50)	8.66 (0.44)	8.79 (0.49)
Subjective Fatigue	0.66 (0.39)	0.93 (0.56)	0.41 (0.48)	0.62 (0.61)
Task Performance	8.97 (0.18)	9.38 (0.14)	8.90 (0.19)	8.52 (0.25)
Response Latency	2.83 (0.12)	2.60 (0.10)	2.72 (0.12)	3.19 (0.12)

4.2. II. Comparison of regression slopes. Although the planned contrast did not reveal a significant effect of listening condition on physiological effort, the descriptive PEP data displayed an interesting pattern, see Figure 19 for a visual representation. The planned contrast modelled a prediction of MIT: the clearly easy task warrants little-to-no effort regardless of reward, as does the unclear task with a low reward, but a high reward in the unclear task justifies more effort investment. Thus, the only condition predicted to have a significant change in PEP was the unclear, high reward listening task. However, although this hypothesis was theoretically driven, it is not possible to know exactly how much effort is required or justified in this listening task. The pattern displayed in the PEP data indicates that a similar level of effort-driven SNS activity occurred in both clearly easy tasks and the unclear high reward task. One could consider that the effort invested in these tasks was either required or justified and effort only falters when the justification is removed (in the unclear, low reward task). Therefore, the null hypothesis that the slope of PEP decrease from the low reward to the high reward conditions remains the same in both the clearly easy and the unclear listening tasks was tested. Two separate regression analysis were conducted on the data from the clear and unclear tasks. The data were treated, for the purpose of the analysis, as independent samples to meet the required assumptions for a linear regression. The low reward tasks acted as the predictor variable, and the high reward tasks were considered the outcome variable. Following a method outlined by Wuensch (2016), the researcher computed the standard error of the difference between slopes using the pooled residual variance from both regression analyses and employed the Student's *t* as the test statistic (method also seen in Weaver & Wuensch, 2013). Yet, the regression coefficients did not significantly differ from one another, $t(28) = 0.56$, $p = .29$.

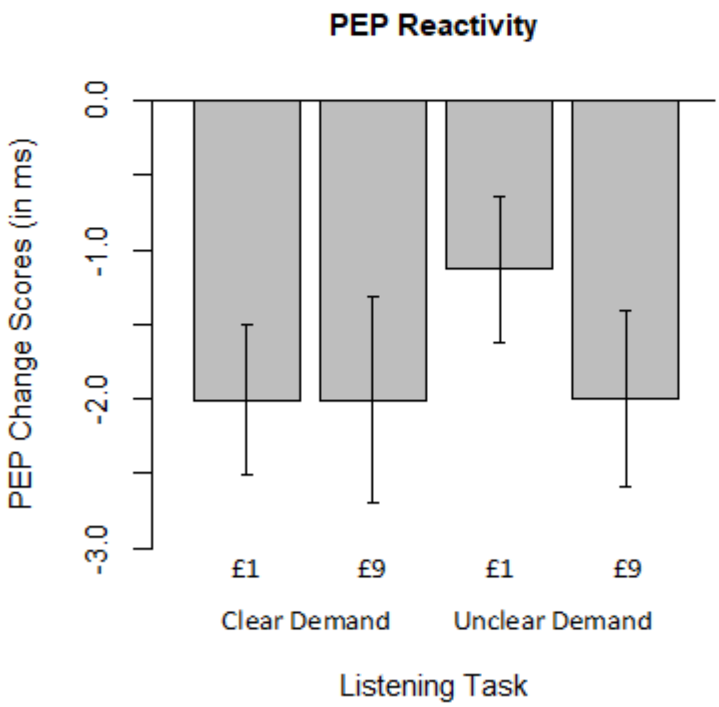

Figure 19.

Mean PEP-q Change Scores in the Four Conditions of the SiWN-Easy. Error Bars Represent Standard Errors. PEP Indicates Pre-Ejection Period

4.2. III. Correlations. Separate correlations were conducted within each listening condition, to investigate the relationship between physiological effort, and subjective effort and fatigue, and task performance. The aim was to explore if fatigue is more likely related to effort-driven physiological reactivity or subjective effort. In total, 22 correlations were performed. The results will first be reported without controlling for the number of tests, then after controlling for the number with a Bonferroni correction. For the Bonferroni, the .05 p-value is replaced with a new p-value which is calculated by dividing the original alpha-value (α-original = .05) by the number of comparisons (22): (α-altered = .05/22) = .02. In the clearly easy task, there were no consistent correlations between the physiological measures and self-reports or task performance. The only significant correlation was found in the clearly easy, high reward condition, where RSA was found to be positively correlated with subjective effort (r = .31, n = 58, p = .05); the weak correlation suggested that decreases in RSA (associated with effort-driven PNS withdrawal) may relate to lower self-reported effort. However, self-reported effort was positively correlated with self-reported fatigue in the low reward condition (r = .32, n = 58, p = .04) and strongly positively correlated in the high reward condition (r = .49, n = 58, p = .003) of the clearly easy listening task. Indicating that increases in self-reported effort relate to increases in self-reported fatigue. After performing a Bonferroni correction, none of the correlations remained significant.

In the unclear demand listening task, no correlations were found between any physiological, self-report or performance measures in the low reward condition. However, in the high reward unclear task, PEP positively correlated with task performance (r = .40, n = 58, p = .02); suggesting that decreases in PEP (indicative of effort-related SNS activation) relate to poorer speech comprehension. In addition, measures of subjective effort negatively correlated with task performance (r = -.33, n = 58, p = .04), indicating that lower ratings of effort relate to better speech comprehension scores. After performing a Bonferroni correction, only the correlation between PEP and task performance remained. A scatterplot of individual PEP values and task performance can be seen in figure 20.

Individual PEP reactivity and task performance in the high reward unclear task

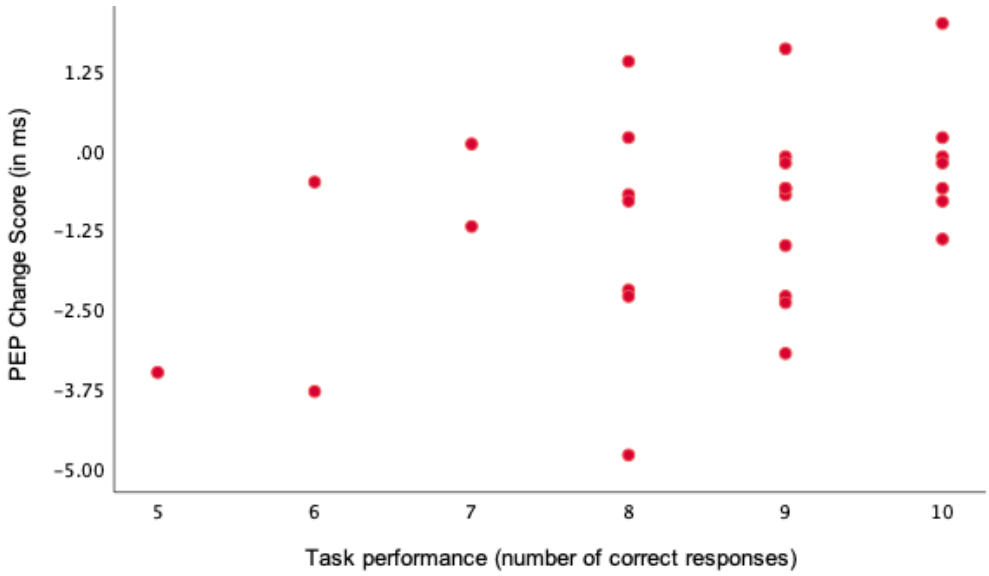

Figure 20.

A scatterplot of individual PEP values and task performance scores within the unclear listening task, with a high reward level.

4.3. Discussion

This study aimed to demonstrate in detail the effect of success importance on listening effort during listening tasks with no clear performance standard. However, ambiguous tasks that could be considered difficult while still being unclear, may demonstrate an interaction effect between task demand and reward, rather than a pure reward effect. Therefore, this experiment created a listening task consisting of trials previously rated as easy in preceding experiments. The task was presented as clearly easy to one group of participants and as unclear to another group in order to show the magnitude of difference in effort investment when task demand is unclear and rewarded compared to clear and rewarded. In the clear task, regardless of reward value, the participants should have invested minimal listening effort, as effort is a function of demand when demand is known, and possible. The same level of effort should be expected in the unclear, low reward task, as the effort is unjustified.

The unclear demand, high reward listening task was predicted to be the only situation wherein more listening effort would be justified, as effort is a function of reward when demand is unknown.

4.3. I. Physiological Reactivity. Specific planned contrasts that modelled the prediction that the only changes in cardiovascular reactivity should occur in the unclear demand-high reward listening task were not significant for any cardiovascular parameters. However, drawing on the descriptive statistics, DBP, HR and SBP all increased in the high reward vs. low reward conditions, but this increase was not different depending on task clarity. As in the previous study, disentangling SNS and PNS influence on these measures proves problematic. Thus, they do not provide evidence for the hypothesis about PNS and SNS driven changes in myocardial activity during effortful listening in response to incentive. Interestingly, the descriptive statistics on PEP data displayed a pattern of reactivity that could be explained by MIT. Decreases in PEP occurred at a similar level in all listening conditions except the unclear demand- low reward task, suggesting that effort investment in this task was unjustified. It is possible that the level of SNS activation, indexed by decreased PEP, was necessary for task success in the clear demand listening task. In the unclear task, only the presence of the high reward incentive justified this level of effort when the listening demand was unknown, leaving effort investment to be unjustified in the unclear demand-low reward listening task. Nevertheless, the difference of PEP reactivity in the low and high reward tasks between the unclear and clear conditions was not significant.

4.3. II. Subjective Measures. Not unlike the physiological findings, the planned contrasts were not significant for subjective effort, fatigue or response latency. Yet, a trend emerged in the descriptive statistics that suggested self-reported effort and fatigue were higher in the high reward compared to low reward listening tasks, but this was not dependant on whether the listening demand was clear or unclear. The planned contrast was significant for listening task performance, likely because the lowest mean performance occurred in the unclear demand-high reward task, in line with the contrast model. Nevertheless, in all four conditions task performance remained above 85%.

4.3. III. Relationship between Physiological Effort, Subjective Ratings and Listening Performance. In the clear demand listening tasks, both low and high reward, no consistent correlations were found between the physiological measures of ANS activity and subjective or performance measures. However, self-reported effort positively correlated with self-reported fatigue with increasing strength as a function of reward when listening demand was both clear and easy. In the unclear demand-low reward listening task, there were no correlations found between any physiological, subjective or performance measures. However, in the unclear demand- high reward listening task, PEP was positively correlated with performance; indicating that increased effort-driven SNS activation was related to poorer speech comprehension.

This experiment provides preliminary evidence that listening effort (SNS activation) occurs as a function of reward when the listening demand is unclear, even if the task stimuli are objectively easy to understand. The study exists to highlight the importance of considering a multitude of factors in understanding effortful listening. Incorporating a variety of perspectives like motivation science and psychophysiological theories enables a comprehensive approach towards the quantification of listening effort and hearing fatigue.

5. Phase Three: Experiments on the Demand-Reward Interaction

5.1. Experiment 5: The effects of task demand and success importance and on effort-driven cardiovascular responses during listening.

Previous experiments within this thesis explored both physiological and subjective effort investment during tasks with clear and unclear demand levels. In accordance with the predictions of MIT (1989) and Wright's active coping hypothesis (1996), SNS-driven myocardial activity indicative of listening effort increased as a function of listening demand, up until the point at which success was not possible, in tasks with a fixed and clear difficulty (see Experiment 2). In another study (see Experiment 3), it was demonstrated that listening effort increases as a function of reward (or success importance) in listening tasks that have unclear difficulty level. Although these studies support the individual effects of demand and success importance on listening effort, MIT predicts the interaction between these parameters determines effort investment in tasks with a clear and fixed difficulty. To ensure conservation of essential resources, the theory suggests that effort is a direct function of demand, if the level of demand is clear and fixed; this ensures that individuals will never invest more than exactly required for success. The importance of success (or potential motivation) has an indirect effect on effort, as it sets the upper limit of the effort-demand relationship (see Figure 21 for MIT's predictions in tasks with clear and fixed difficulty). A number of variables affect the importance of success such as, instrumentality of task success, incentive, and personality traits, which all influence an individual's motivation for a given task. Therefore, drawing on Wright's (1996) integration, myocardial SNS activity should increase as a function of (listening) demand while success is possible, and potential reward (a factor of success importance) should set the upper limit of the effort-demand relationship (Richter, 2013).

Empirical evidence provides support for Wright's (1996) MIT hypothesis that both task demand and success importance determine effort-driven cardiac reactivity during active coping tasks (wherein performance determines the outcome). For example, in a study conducted by Eubanks, Wright, and Williams (2002) participants completed a cognitive task at 5 demand levels, for the possibility of winning either a $100 or $10 prize by achieving a 90% success rate. In the first four difficulty levels, HR increased as a function of difficulty in both the low ($10) and high ($100) reward groups. The only difference emerged at the highest difficulty level where HR reactivity was significantly increased in the high reward group, emphasising that reward only affects effort at high difficulty as it determines the upper limit of the effort-demand relationship (Eubanks et al., 2002). Similarly, in another study where performance on a memory task (easy vs. difficult) determined whether participants avoided either a mild noise (low success importance) or a loud noise (high importance), HR and SBP increased with task difficulty only when success importance was high (Wright, Shaw, & Jones, 1990). Gendolla and Richter (2006) manipulated success importance by making participants answers either public or private, under the premise that the presence of social observation would increase the importance of success. While SBP was proportional to task difficulty for participants under social observation, it remained low regardless of difficulty for participants responding in private (Gendolla & Richter, 2006a). In another study, Gendolla and Richter manipulated success importance by the level of ego-involvement; some participants understood the experimental task served to diagnose the capacity critical for academic success (high ego-involvement), whereas other participants simply believed it to be a cognitive task (low ego-involvement). SBP and DBP increased as a function of difficulty when ego-involvement was high but remained low when ego-involvement was low (Gendolla & Richter, 2006b).

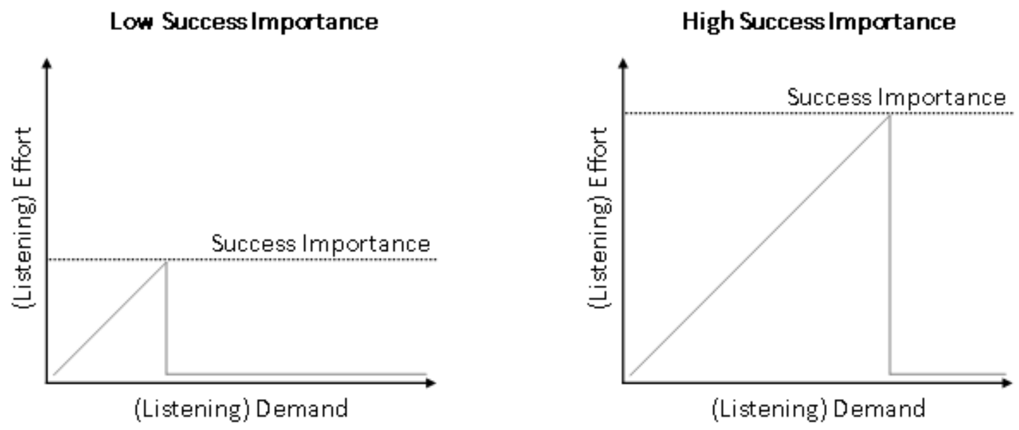

Figure 21.

MIT's predictions for tasks with a clear and fixed demand level.

Other researchers looked at alternative determinants of success importance, like personality type, to test the impact of these individual factors on the upper-limit of effort investment in active coping. Findings revealed that high self-focused attention increases SBP during experimental tasks that are difficult as opposed to easy (Silvia et al., 2010). In another study, need for closure (NFC) had a similar effect on effort-related cardiac activity; if task difficulty was low, PEP was low regardless of NFC, but if the task was difficult, PEP reactivity increased only for individuals with high NFC (Richter et al., 2012). All the aforementioned studies provide evidence according to Wright's (1996) integrative hypothesis that effort-related cardiac activity increases as a function of demand, but only while effort is justified. The studies highlight that in demanding tasks, the effort-demand relationship is limited by success importance; which can be influenced by many factors including, incentive, task context and personality.

Importantly, due to the reliance on Wright's (1996) perspective (like much of the other research on MIT mentioned previously within this thesis), most of the studies interested in the joint impact of demand and reward on effort focused exclusively on measures of sympathetic myocardial activity to index effort. The resultant evidence that supports the predictions of MIT thus provides a limited perspective of the physiological correlates of effort investment, as no evidence is given as to the reactivity of the other half of the ANS. The PNS has been suggested to have an essential role in effort investment during physical activity, and its function has also been highlighted in other psychological theories and research on cardiac regulation during effortful activity (for examples see, Berntson, Cacioppo, & Quigley, 1991; Robinson, Epstein, Beiser, & Braunwald, 1966; White & Raven, 2014). In order to provide a holistic view of myocardial activity during effortful listening, it would be valuable to consider the role of both the SNS and PNS.

Although studies on effortful listening have on occasion employed measures of PNS activity as indicators of effort (e.g. Mackersie & Calderon-Moultrie, 2016; Mackersie, Macphee, & Heldt, 2015); these studies did not utilise theories of effort or consider motivational factors beyond task difficulty in determining effort investment during listening. The research on MIT shows that effort occurs not only as a function of demand but is indirectly determined by the importance of success, which encompasses numerous motivational factors. Researchers in the listening effort field have begun to acknowledge the role of motivation in listening effort (Pichora-Fuller et al., 2016) and a couple of empirical studies have explored the joint effects of demand and incentive on listening effort. For example, Richter (2016) conducted a study wherein participants completed four blocks of an auditory discrimination task (low reward- low demand, low reward- high demand, high reward- low demand and high reward- high demand). In line with MIT, PEP reactivity was highest during the high demand- high reward task compared to the other 3 conditions; suggesting that the presence of a reward increased the potential motivation for the highly demanding listening task (Richter, 2016b).

This fifth and final experiment served to investigate the effect of the interaction between known task demand and the importance of success (or reward incentive) on listening effort. Previous studies within this thesis have found that measures of SNS activation (PEP) increase as a function of listening demand (see Experiment 2) and as a function of reward when listening demand was unclear (see Experiment 3). This study attempted to integrate these findings to investigate the effect of the demand-reward interaction on effort-related SNS activity (PEP). The effect of the demand-reward interaction on PNS activation using RSA while controlling for respiration rate was also measured. By enhancing the measurement of RSA through controlling the influence of respiration rate a more accurate measure of PNS activity can be obtained than in previous studies within this thesis. This final study predicts that the relationship between listening demand and invested effort is moderated by whether the required effort is justified by the importance of successful speech comprehension.

5.2. Method

5.2. I. Participants and Design. The sample consisted of 47[7] adults, 28 females and 19 males with a mean age of 28.94 years, with no clinically diagnosed hearing impairment and without pacemakers. Emails, social media and poster adverts displayed at Liverpool John Moores University recruited the individuals who took part. The research remunerated all participants with a £5 GBP Amazon Voucher for their time. Each participant was systematically assigned to one of two groups: reward or no reward. Within each group, the participant completed four demand

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[7] Sample size was determined using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) setting alpha error to 5%, beta error to 5% and f to 0.25.

conditions of a speech in pure white noise task (SiWN): low, moderate, high and impossible, in a systematically randomised order. In the rewarded group, participants could receive an extra £2 in Amazon Vouchers in each of the listening tasks as an incentive for successful task performance. Whereas those in the no reward group, would not receive any monetary incentive.

It was predicted that participants who competed the listening tasks without a reward incentive (or where success held less importance) would invest a reduced amount of effort (as indicated by cardiac reactivity, specifically PNS withdrawal and SNS activation) in the highly demanding listening task, as the required effort would not be justified by a beneficial outcome. It was predicted that in the un-rewarded low to moderate demand listening tasks, small amounts of increasing effort investment, as the required effort is not so high as to become unjustified. In the un-rewarded high and impossible demand listening tasks, disengagement of listening effort was predicted. Whereas, in listening tasks offering a reward incentive (or where success importance is higher), increased listening effort should be invested in the listening task with a high demand because it is justified by the benefit of a reward. Like in the un-rewarded condition, disengagement of listening effort should occur in the rewarded impossible demand task because success is not achievable, and no amount of reward could change the possibility of success.

5.2. II. Procedure. Inquisit by Millisecond Software (Seattle, WA) controlled the presentation of the experimental stimuli and collected participant's responses. Each participant took part independently and provided informed written consent. The researcher recorded the height and weight of the participant and attached four pairs of electrodes from an impedance cardiograph (Medis Medizinische Messtechnik GmbH, Illmenau, Germany) to the sides of the participant's neck and chest. The cardiograph sampled an ECG and ICG at a rate of 1000Hz; these signals calculated PEP and RSA to quantify SNS and PNS activity and, to calculate HR. A blood pressure cuff from a Dinamap Carescape V100 monitor (GE Healthcare, Buckinghamshire, UK) fastened to the participant's upper left arm measured SBP and DBP using the oscillometric method at two-minute intervals. HR and DBP controlled for changes in cardiac preload and afterload.

RSA is a source of heart rate variability related to respiration, also referred to as HF-HRV, reflecting the 0.15- 0.4 Hz band that is typical of respiratory frequency. However, when using RSA as an indicator of parasympathetic activity one must consider that fluctuations in breathing rate can have an effect on the measurement of RSA (Grossman, 2004; Grossman & Taylor, 2007). Therefore, the researchers monitored respiration to control for its possible influence on RSA using two BioPac SS5LB respiratory effort transducers worn over the participant's clothes, one at the chest and the other around the abdomen (BIOPAC Systems Inc., Goleta, CA, USA). The elasticised belts measured the change in thoracic and abdominal circumference using a BIOPAC MP30 system, sampling the signal at 50Hz.

While the participant sat at the testing computer, the researcher verbally explained the experimental structure and encouraged the participant to read the on-screen instructions before beginning the experiment. It was at this point that the participant learnt their condition assignment (reward vs. no reward). Those in the reward condition were informed that they could earn an extra £2 Amazon Voucher in each of the four listening tasks, if they were able to respond correctly in 7 out of 10 trials in each task. Those in the no reward group simply learnt that they would not receive any reward for responding correctly.

The participant entered their demographic information (age and gender) and completed a pre-test fatigue questionnaire. The 9-item questionnaire was the same as had been used in the three previous studies within this thesis, wherein the participant selected a word from two comparative adjectives (one describing tiredness and the other wakefulness) that best described their current state. After this they completed the first block of the experiment, within each block the participant would complete two practice trials of the listening task, a 6-minute baseline, the listening task (consisting of 10 trials), and two post-task self-reports. The task was the same SiWN task used in the second experiment of this thesis. The task required participants to listen to a 32-second short story (50dB) in the presence of some background white noise, the white noise was presented at -36dB lower than the speech in the low demand task, at -15dB in the moderate condition, at -9dB in high demand condition, and at +3dB higher in the impossible condition. After hearing the story, the computer presented the participant with a comprehension question, three possible answers and a 5-second timer, the participant was required to select an answer within the response window. In the preceding practice trials, the participant received feedback (correct answer/ incorrect answer) after responding. After the practice trials, the participant rested for a 6-minute baseline. During this period the participant watched an origami tutorial video, the clip contained quiet music but no speech. During this time, the researcher recorded an ICG and ECG and the respiratory signal from the breathing belts. The researcher also recorded measurements of SBP and DBP at 2-minute intervals after the first 60 seconds of the video.

When the video ended, the participant viewed the task instructions for a second time and was either reminded that they should aim for a 7/10 performance standard (no reward group) or that they would earn a £2 Amazon Voucher if they achieved a 7/10 performance standard (reward group). Then they completed a SiWN task block consisting of 10 randomised trials at the same level of listening demand as the preceding practice trials (either low, moderate, high or impossible demand). The researcher measured an ICG, ECG and respiration signals throughout the task, and SBP and DBP values at 2-minute intervals. The participant did not receive feedback on their answers at this time. After completing the task block, the participant answered the 9-item fatigue questionnaire again and the mental demand and effort items from the NASA-TLX (Hart & Staveland, 1988). The participant then repeated this entire procedure for the remaining three task blocks until they had completed all demand levels of the SiWN task. Upon conclusion of the experiment, the participant received on-screen feedback indicating their scores on the four tasks. All participants were remunerated with a £5 Amazon Voucher for their time and those in the rewarded group received the extra vouchers earned for their task performance.

5. 2. III. Data Analysis.

5.2. III. a. Physiological Data Analysis. For the analysis of the ICG, ECG, and respiratory signals, the researcher used the data from last 5-minutes of each baseline period and the first 5-minutes of each task period, as in all prior experiments in this thesis. PEP quantified SNS reactivity in the same way as in the previous experiments. Two independent raters scored the PEP values (the interval between the Q-point on the ECG and the B-point on the ICG in milliseconds). Because the interrater agreement was good (intraclass correlation [ICC] [2,1] = > .92), the arithmetic mean of both raters' PEP values was used for the statistical analyses. Change scores between task and baseline values of PEP quantified the change in SNS activity. Myocardial PNS reactivity was quantified as RSA by the same method as in previous experiments; by firstly detecting all R-peaks offline in BlueBox (Richter, 2009), and subsequently conducting a FFT frequency domain analysis in Kubios (Tarvainen et al., 2014). The respiratory data was analysed in BioPac Student Lab 4.0 (BIOPAC Systems Inc., Goleta, CA, USA). The software calculated the mean, maximum, minimum and standard deviation of respiration rate (in Hz) from the combined respiratory waveform (arithmetic mean of thoracic and abdominal respiration) for all periods. The researchers identified ten participants with a mean respiratory frequency outside the 0.15-0.40 Hz band; the subsequent statistical analyses on the RSA data did not include these participants. The change score between task and baseline values of RSA determined the change in PNS activity. The mean HR was also calculated in Kubios. Averaged SBP and DBP values recorded during the baselines and tasks produced mean values of SBP and DBP for each period. The change scores between task and the respective baseline values for HR, SBP and DBP were calculated. HR and DBP were collected to control for cardiac loading effects on PEP.

Mixed model planned contrasts were used to test the hypothesis about the limiting effect of success importance on the listening effort- listening demand relationship. Each of the eight experimental conditions were assigned to contrast weights modelling a specific prediction for each statistical analysis. For the PEP data these weights modelled and exponential increase in SNS activity during the three possible and rewarded listening tasks (-1.25, 0.75, 4.75) and no activity in the impossible and rewarded task (-1.25). In the non-rewarded listening tasks, participants were expected to disengage sooner as the effort would not be justified in the highly demanding task, thus the weights modelled an exponential increase in SNS reactivity in the low and moderate tasks (-1.25, 0.75) and disengagement in the high and impossible tasks (-1.25, -1.25). For the RSA data, the weights modelled an exponential decay in PNS activity while success was possible and justified (rewarded listening: low demand 1.75, moderate -2.25, high -4.25, and impossible 1.75, non-rewarded: low 1.75, moderate -2.25, high 1.75 and impossible 1.75). For the other cardiac measures weights, -1, 1, 3, -1 and -1, 1, -1, -1, were used in the rewarded and non-rewarded conditions respectively, as these model a linear increase and disengagement in tasks where effort was not justified. For a list of all contrasts used in this experiment, see Table 15.

5.2. III. b. Subjective and Performance Data Analysis. The total number of correct answers and average response time in each task quantified listening performance and response latency. The sum of responses given on the two NASA-TLX items quantified subjective effort. For subjective fatigue, the researchers calculated change scores for each condition by subtracting the post-task responses on the 7-item fatigue questionnaire from the pre-test score.

The effect of the listening demand-reward interaction on task performance and response times was tested using a linear contrast in all the reward and non-reward conditions (-3, -1, 1, 3). For subjective effort and fatigue the contrast weights, -1, 1, 3, -1 and -1, 1, -1, -1, were used in the rewarded and non-rewarded conditions respectively, as these model a linear increase and disengagement in tasks where effort was not justified.

Table 15.

Contrast Weights For All Experimental Conditions and Dependant Variables.

		Listening Demand			
		Low	Moderate	High	Impossible
SNS Reactivity	No Reward	-1.25	0.75	-1.25	-1.25
	Reward	-1.25	0.75	4.75	-1.25
PNS Reactivity	No Reward	1.75	-2.25	1.75	1.75
	Reward	1.75	-2.25	-4.25	1.75
Cardiac Activity, Self-Reports	No Reward	-1	1	-1	-1
	Reward	-1	1	3	-1
Task Performance	No Reward	-3	-1	1	3
	Reward	-3	-1	1	3

5.3. Results

5.3. I. Planned Contrasts.

5.3. I. a. Cardiovascular Response. The planned contrast indicated that the demand-reward interaction did not have a significant effect on listening effort-driven SNS activity (PEP) $t(45) = 0.57$, $p = .29$. Similarly, the contrast analysis showed that the predicted interaction between listening demand and reward did not have a significant effect on PNS reactivity, quantified by RSA, $t(35) = 0.07$, $p = .41$. The planned contrast for the predicted effect of listening condition on total ANS activity was not significant, $t(35) = 0.46$, $p = .32$. The predicted listening demand-reward interaction did not have a significant effect on SBP as indicated by the planned contrast, $t(45) = 0.07$, $p = .41$. The planned contrasts for DBP and HR (collected to control for loading effects on PEP) were not significant, $t(45) = 0.04$, $p = .48$ and $t(45) = 1.54$, $p = .07$ respectively. Table 16 displays the means and standard errors.

Table 16.

Change Score Means and Standard Errors (in Parentheses) of Cardiovascular Responses During the Eight Listening Demand Conditions of the SiWN.

		Listening Demand			
		Low	Moderate	High	Impossible
PEP	No Reward	-1.60 (0.67)	-0.41 (0.57)	-1.41 (0.85)	-0.36 (0.49)
	Reward	-1.02 (0.75)	0.79 (0.96)	-0.56 (0.73)	0.33 (0.58)
RSA*	No Reward	-0.51 (2.29)	3.57 (2.92)	-4.78 (3.03)	-1.00 (2.50)
	Reward	-7.01 (1.92)	-4.71 (2.43)	-6.51 (3.06)	-4.71 (3.01)
ANS*	No Reward	0.21 (0.30)	-0.38 (0.23)	0.56 (0.23)	0.05 (0.30)
	Reward	0.96 (0.35)	0.26 (0.29)	0.52 (0.27)	0.24 (0.35)
SBP	No Reward	1.49 (1.02)	1.04 (0.60)	0.75 (0.89)	-0.83 (1.15)
	Reward	2.35 (2.07)	2.76 (1.12)	1.69 (0.95)	-0.42 (0.63)
DBP	No Reward	0.28 (0.59)	0.95 (0.68)	-0.06 (0.59)	-0.09 (0.60)
	Reward	0.18 (0.79)	1.33 (0.84)	-0.75 (0.66)	-0.17 (0.64)
HR	No Reward	0.74 (0.42)	1.58 (0.53)	1.13 (0.41)	1.06 (0.46)
	Reward	2.20 (0.57)	3.22 (0.58)	1.56 (0.53)	1.25 (0.50)

*Note: The means and standard errors for RSA and ANS were from the sample of 36 individuals (no reward n = 16, reward n = 21) after the exclusion of 10 cases wherein respiratory frequency occurred outside of the 0.15-0.40 range.

5.3. I. b. Subjective and Performance Data. The planned contrast modelling the prediction of MIT was significant for the effect of the listening demand-reward interaction on subjective effort, $t(45) = 3.96$, $p < .001$, but not subjective fatigue, $t(45) = 0.72$, $p = .24$. Linear contrasts showed that listening performance diminished as a function of demand in both the reward and no reward conditions, $t(45) = 14.73$, $p < .001$. The contrast analysis also found slower response times as a function of listening demand in both reward conditions, $t(45) = 4.02$, $p < .001$. All means and standard errors for the subjective and performance measures are given in Table 17.

Table 17.

Change Score Means and Standard Errors (in Parentheses) of Self-Reports and Task Performance During the Eight Listening Demand Conditions of the SiWN.

		Listening Demand			
		Low	Moderate	High	Impossible
Subjective Effort	No Reward	3.78 (0.30)	5.96 (0.43)	7.87 (0.34)	7.91 (0.50)
	Reward	4.01 (0.46)	6.58 (0.49)	8.83 (0.32)	8.67 (0.49)
Subjective Fatigue	No Reward	0.87 (0.62)	2.22 (0.79)	2.48 (0.85)	2.13 (0.76)
	Reward	0.54 (0.63)	1.71 (0.93)	2.42 (0.93)	2.83 (0.89)
Task Performance	No Reward	9.13 (0.31)	7.57 (0.36)	7.22 (0.51)	3.57 (0.43)
	Reward	9.63 (0.13)	7.25 (0.40)	6.58 (0.45)	3.67 (0.35)
Response Time	No Reward	1.27 (0.18)	1.51 (0.18)	1.57 (0.24)	1.97 (0.28)
	Reward	1.11 (0.83)	1.53 (0.15)	1.75 (0.13)	1.94 (0.22)

5.3. II. Correlations of Physiological Measures during Incentivised Listening. In total, 44 correlations were performed. The results will first be reported without controlling for the number of tests, then after controlling for the number with a Bonferroni correction. For the Bonferroni, the .05 p value is replaced with a new p-value which is calculated by dividing the original alpha-value (α-original = .05) by the number of comparisons (44): (α-altered = .05/44) = .001. There were no consistent correlations between SNS activity, as measured by PEP, and the subjective or performance measures in the rewarded listening tasks. PEP correlated with self-reported fatigue in two rewarded listening tasks. A weak negative correlation emerged in the rewarded- high demand task (r = -.37, n = 24, p = .04), indicating that the lower the PEP (SNS activation), the higher the fatigue. In addition to a weak positive correlation in the rewarded- impossible demand task (r = .36, n = 24, p = .04), suggesting that the lower the PEP, the lower the fatigue. A strong positive correlation between PEP and task performance in the rewarded- impossible demand task was found (r = .52, n = 24, p = .005), signifying that the lower the PEP, the poorer the performance. There were no significant correlations between PNS reactivity, quantified by RSA, and subjective or performance measures in any of the rewarded listening tasks. After Bonferroni correction, there were no significant correlations of physiological measures during incentivised listening.

5.3. III. Correlations of Physiological Measures during Un-Rewarded Listening. In the non-rewarded tasks, a greater number of significant correlations were found between physiological reactivity and subjective and performance measures, yet they still appeared to be unsystematic. For SNS activation, PEP did not correlate with subjective fatigue, but did show a weak positive correlation with subjective effort in the no rewarded- impossible task only (r = .37, n = 23, p = .04), suggesting the lower the PEP (SNS activation), the lower the subjective effort. A strong positive correlation emerged between PEP and task performance in the no reward- high demand task (r = .56, n = 23, p = .003), indicating that the lower the PEP, the lower the performance. Significant correlations emerged more consistently between PEP and response time in the non-rewarded tasks, the measures correlated negatively in most listening conditions, except in the low demand task. This suggests that the lower the PEP (increased SNS activation), the slower the response time (moderate demand: r = -.46, n = 23, p = .01, high demand: r = -.57, n = 23, p = .002, and impossible demand: r = -.50, n = 23, p = .007). For PNS reactivity, RSA did not significantly correlate with either subjective effort or fatigue. However, a strong negative correlation emerged between RSA and task performance in the no reward- high demand task (*r* = -.62, *n* = 23, *p* = .005), suggesting that the lower the RSA (PNS withdrawal), the higher the performance. A weak negative correlation occurred between RSA and response time in the no reward- impossible demand task (*r* = -.44, *n* = 23, *p* = .04), suggesting the lower the RSA, the slower the response time. After Bonferroni correction, there were no significant correlations of physiological measures during un-rewarded listening.

5.3. IV. Correlations of Subjective Measures during Incentivised Listening. A single significant correlation emerged between subjective effort and subjective fatigue in the rewarded- moderate demand task (*r* = .54, *n* = 24, *p* = .003), indicating a strong positive relationship between self-reported effort and fatigue during rewarded listening, at a moderately demanding level. After Bonferroni correction, there were no significant correlations of subjective measures during incentivised listening.

5.3. V. Correlations of Subjective Measures during Un-Rewarded Listening. In contrast, weak positive correlations emerged between subjective effort and fatigue in the majority of non-rewarded listening tasks, apart from the high demand listening task (low demand: *r* = .37, *n* = 23, *p* = .04, moderate demand: *r* = .36, *n* = 23, *p* = .04, and impossible demand: *r* = .43, *n* = 23, *p* = .02). In the no reward- moderate demand task, self-reported effort was negatively correlated with task performance (*r* = -.40, *n* = 23, *p* = .03) as well as positively correlated with response time (*r* = .39, *n* = 23, *p* = .03); indicating that the higher the subjective effort, the more performance faltered in both accuracy and efficiency. A strong negative correlation was found between self-reported effort and response time in the no reward- impossible demand listening task (*r* = -.51, *n* = 23, *p* = .007). After Bonferroni correction, there were no significant correlations of subjective measures during un-rewarded listening.

5. 4. Discussion

This study aimed to show that listening effort is a direct function of listening demand, but is also indirectly determined by the importance of successful speech comprehension, which limits the listening effort- listening demand relationship. Guided by MIT, listening effort (quantified as PNS withdrawal and SNS activation) was predicted to increase with listening demand while the task is possible and the required listening effort is justified. Considering this, an increase in listening effort should occur from the low demand to the moderate demand SiWN condition regardless of incentive. Yet when the listening demand is high, the participants in the rewarded group should expend more effort than those in the no reward group, because the reward incentive increases the importance of success. In the impossible listening tasks, listening effort should be low regardless of reward.

5. 4. I. Physiological Reactivity.

The planned contrasts modelled the prediction that effort should increase with demand while success was possible and justified. In the rewarded tasks, listening effort should increase over the three possible listening tasks and be low in the impossible task. However, in the no reward tasks, listening effort should increase over the first two listening demand conditions and be low in the high and impossible tasks. The contrast analysis was not significant for the listening demand- reward interaction effect on any of the physiological parameters. This suggests that cardiovascular (CV) reactivity did not follow the predictions of MIT in this study, as the potential reward for successful performance in the high demand listening task did not produce significant increases in CV reactivity compared to no reward. Drawing on the descriptive statistics, the highest level of PEP reactivity occurred during the low demand listening task in the no reward and reward conditions, representing increased effort-driven beta-adrenergic myocardial activity during ‘easy’ listening. If PEP is an efficacious indicator of effort investment, one could suggest that the listening effort required in the moderate, high and impossible tasks was too high to be justified, even in the presence of a reward. Foreseeing how participants appraise both demand and reward is problematic and many factors influence this, such as mood and personality, which can change how individuals view a task. For example, individuals with depressive symptoms are less likely to increase effort investment as a function of reward than healthy participants (Brinkmann & Franzen, 2013). In this study, participants were aware of group assignment, which may have affected their effort investment. The maximum level of effort that the participants were willing to invest (success importance) in the no reward condition could have decreased upon finding out that they would not be receiving the potential rewards. Similarly, participants in the rewarded listening condition may have viewed £2 as a low incentive, thus reducing the level of success importance. A previous study within this thesis (Experiment 3) employed a £2 incentive amount wherein it constituted a ‘low reward’ listening task. In Experiment 3, PEP increased as a function of reward, with the lowest levels of reactivity occurring the in no reward and low reward (£2) tasks, it was not until reward values of £4 and £6 were available that PEP significantly decreased (see Experiment 3). Furthermore, another study on effortful listening also found that the presence of reward had no impact on effort-driven SNS activation in the pupil response (Koelewijn et al., 2018); however changes in pupil size can also reflect decreases in parasympathetic innervation, therefore this result should be interpreted with caution.

The lack of evidence to support PNS withdrawal during effortful listening is much less surprising, as previous studies within this thesis display similar findings; PNS withdrawal (indicated by RSA) did not occur as a function of either listening demand (Experiment 2) or reward (Experiment 3). However, this final study intended to improve the quantification of PNS reactivity using RSA by controlling for respiration.

In doing so, the researchers removed several participants from the statistical analysis; it is thus possible that the sample size was too small to elicit a significant effect of the demand- reward interaction on PNS reactivity. However, the descriptive statistics indicate that decreases in RSA tended to be stronger in the rewarded than unrewarded listening tasks, suggesting possible PNS withdrawal indicative of effort during rewarded listening.

Although the contrast analyses were not significant for the interaction effect of reward and demand on SBP, DBP or HR, the descriptive statistics display an interesting trend. In the rewarded listening tasks, SBP is seen to increase from the low to moderate demand task and decrease in the in the high demand and impossible tasks. In the non-rewarded tasks, SBP reactivity is lower in all conditions compared to the rewarded tasks, yet it is highest in the low demand condition and then systematically decreases over the moderate, high, and impossible listening demand tasks. The HR and DBP descriptive statistics also display this pattern. The corroborating evidence from HR, DBP and SBP indicate a trend towards a pattern of cardiovascular reactivity that partially supports the research predictions. CV reactivity increased when task demand was both possible and justified (in the rewarded low and moderate listening demand tasks) and was lower in the remaining conditions that were either not justified due to low success importance or not possible. This perspective suggests that the £2 reward was not high enough as to increase success importance in the high demand listening task. However, these measures are problematic if one wishes to understand the relative contributions of the SNS and PNS towards cardiac regulation during effortful listening, as both branches of the ANS influence their reactivity. Of these CV measures SBP is likely the most reliable indicator of SNS activation because it is more influenced by myocardial contractility than DBP or HR. Drawing on this perspective many previous researchers used SBP to quantify beta-adrenergic activity to test the predictions of MIT (for examples see, Gendolla & Krüsken, 2001, 2002; Silvia et al., 2010; Wright et al., 1990). Similarly, other studies employed HR to provide evidence for the effect of the demand-reward interaction on cardiovascular activity, and interpreted the results as evidence for effort investment during active coping (Eubanks et al., 2002).

Although MIT provides researchers with guideline predictions for effort-based research, many factors influence success importance (or potential motivation) and thus effort investment in activities. For example, personality factors, achievement motive, mental health and mood all affect the level of success importance (Brinkmann & Franzen, 2013; Capa et al., 2008; Gendolla, Brinkmann, & Silvestrini, 2012; Silvestrini & Gendolla, 2011). Furthermore, the appraisal of rewards may differ among participants with some placing greater value on monetary reward, thus affecting their motivation for the task.

5.4. II. Subjective and Performance Measures. Although the planned contrast suggested that the demand-reward interaction did not have the predicted effect on subjective fatigue, it did have the predicted effect on subjective effort. Suggesting that even if there was a lack of evidence for the physiological indictors of effort, the individuals in this study experienced increases in subjective effort as a function of demand and reward. Many other studies also observed inconsistencies between the manifestations of physiological and subjective effort, finding that they are rarely correlated (for examples in listening effort researh see, Mackersie & Cones, 2011; Seeman & Sims, 2015). A fundamental difference between these measures may explain the conflicts between physiological and subjective data. Subjective reports, unlike physiological reactivity, is reliant on the perceptions of the participant (McGarrigle et al., 2014); their understanding of the self-report (knowledge); their propensity towards response bias; or their introspective abilities (Kuchinsky et al., 2013). Many of these factors are outside of experimental control and can influence subjective ratings, while objective measures remain unaffected.

Both listening performance and response latency became poorer and less efficient across the four listening demand conditions in both the rewarded and not rewarded groups of listeners. These findings could indicate a successful manipulation of listening demand, but reward did not significantly alter the relationship between demand and performance.

5.4. III. Relationship between Physiological Effort, Subjective Ratings and Listening Performance. Particularly in the rewarded listening tasks, the correlations between physiological measures and subjective ratings and task performance were unsystematic. This study found little evidence to support any relationship between objective and subjective markers of effortful listening in the presence of reward. A larger number of significant correlations emerged between the objective and subjective measures when the listening tasks were not rewarded. There appeared to be a systematic negative correlation between PEP and response latency, which increased in strength in the most demanding listening tasks. Suggesting that within each condition, the lower the PEP (increased SNS activation) the slower the response time. This finding could suggest that increases in effort-driven myocardial activity occurred alongside decrements in task performance due to high demand. To maintain overall performance, participants may have become less efficient, which could also indicate task related fatigue. These correlations may have emerged in the no reward condition only because the presence of reward in the other tasks alters the relationship between effort and performance decrements, possibly by offsetting performance related fatigue (Hockey, 2011).

This final experiment aimed to provide a holistic evaluation of the physiological correlates of effortful listening guided by the predictions of MIT. The research was grounded in evidence from previous studies within this thesis, which suggested effortful listening is based not only on demand but also on motivational factors (i.e.

reward). Listening effort was predicted to occur as a function of demand while success is both possible and the required effort is justified by the importance of success. The results highlighted a trend of cardiovascular reactivity (indicated by SBP, HR and DBP) that provided partial support for this hypothesis. However, this study failed to provide statistical evidence for listening effort (quantified as PNS withdrawal and SNS activation) in response to listening demand and incentive. Nevertheless, there was a significant interaction effect between demand and reward on subjective listening effort. The findings promote the perspective that listening effort is not only caused by difficulty during hearing but by fluctuations in the motivation to listen.

III. Discussion Chapters

1. A General Discussion of the Findings

1.1. The impact of listening demand on effort-driven myocardial activity

The first stage of experiments in this thesis aimed to test the hypothesis (based on MIT) that listening effort (operationalised as PNS withdrawal and SNS activation) should increase as a function of listening demand while comprehension is possible. In addition, increases in subjective effort and fatigue were predicted to accompany the observed changes in cardiovascular reactivity.

1.1. I. Experiment 1. Experiment 1 aimed to investigate the effect of a simple listening demand manipulation on listening effort. The results provided weak evidence in support of the hypothesis, as the specific cardiac measures of SNS and PNS activity did not display the predicted pattern. There were however significant increases in SBP, a previously popular measure in the empirical research on MIT, that has been used to indicate myocardial SNS activity (Contrada et al., 1984; Gendolla & Krüsken, 2002; Richter et al., 2008; Wright et al., 1986). However, peripheral resistance that is not under beta-adrenergic control influences SBP. This result should be interpreted with caution, as SBP may constitute a poor indicator of myocardial SNS activity. In secondary analyses, it became evident from the participant's listening performance that the manipulation of listening demand may have been unsuccessful in this study. The listening task required participants to hear and subsequently identify single words. Tasks comprising short-lasting stimuli are not unheard of in listening effort research, but it is more typical for longer listening tasks to be employed (for example, sentences in noise tasks: Koelewijn, de Kluiver, Shinn-Cunningham, Zekveld, & Kramer, 2015; Zekveld, Rudner, Kramer, Lyzenga, & Rönnberg, 2014). Utilising a task that requires only short bursts of effort investment results in limitations for the measurement of effort in listening. For example, a noticeable flaw is the lack of ecological validity, as short-term effort investment is not representative of the demanding situations hearing-impaired individuals manage. Furthermore, the short bursts of effort investment likely allowed participants to 'rest' for half of the task period, during the response window, and while waiting for stimulus presentation. Therefore, even if the difficult task was effortful, participants only had to invest this effort for very short amounts of time and could spend a lot of time recovering (both cognitively and physiologically).

1.1. II. Experiment 2. The findings from the initial study, although with its limitations, provided valuable evidence that informed and improved the design of the following experiments within this thesis. The researchers consequently devised a listening task manipulating demand by varying the level of pure white noise during a 32-second segment of speech. Experiment 2 utilised this new listening task (the SiWN) and provided empirical evidence for the impact of listening demand on effort-driven myocardial activity during listening while comprehension was possible. PEP, the 'gold standard' for non-invasive measures of myocardial activity, decreased significantly over three possible listening demand conditions in the SiWN and remained unaffected in the impossible listening task. This finding provides evidence that beta-adrenergic SNS myocardial activity increases as a function of listening demand while success is impossible. When successful listening is impossible, individuals disengage effort. This finding is congruent with numerous studies relying on Wright's (1996) integrative approach (see Richter et al., 2008 for an example). Studies on listening effort have also found an inverted U-shaped relationship between task demand and listening effort. For example, one study found that peak pupil dilation (a SNS influenced measure) was at maximum during moderately demanding listening, but when listening demand was low or too high, peak pupil dilation was significantly smaller (Ohlenforst, Zekveld, Lunner, et al., 2017). In further support of the disengagement hypothesis, likelihood ratios indicated that the PEP data was more likely to occur under the MIT hypothesis that predicts disengagement when the task is impossible, than under an alternative linear hypothesis, that predicts increases in effort regardless of the possibility of success.

Increases in subjective fatigue and effort were predicted to increase alongside autonomic activation during listening. This hypothesis was partially supported as subjective effort ratings significantly increased with listening demand while success was possible (in Experiment 1 as well as 2). In addition, response latency slowed with demand, which other researchers interpreted as evidence for objective fatigue (e.g. Hornsby, 2013). Interestingly, the subjective effort data was more likely under a linear model compared to MIT's prediction that effort is limited by the possibility of success. Suggesting that subjective effort is more likely to occur as a function of listening demand, regardless of whether successful comprehension is possible. This finding indicates a discrepancy between physiological and subjective effort in listening tasks with an impossible level of demand. Yet, inconsistencies between subjective and objective measures of effort are not uncommon in the listening effort research (for example, Mackersie & Cones, 2011; and Picou & Ricketts, 2018)

Interestingly, listening performance showed the most variation in the impossible demand condition; the larger standard error could indicate that some individuals give up while others continue trying. Some researchers suggest that cognitive ability might affect whether individuals continue to engage effort (Zekveld et al., 2011). Correlations were conducted within each demand condition to see if variations in subjective effort, fatigue or physiological reactivity were related to one another or related to variations in task performance. Yet there appeared to be no consistent correlations, indicating that there is no evidence for a systematic relationship between any of these variables. Understanding how hearing fatigue and decrements in listening performance manifest in relation to effortful listening warrants future research. These research efforts may be best focused on the hearing-impaired population in the real world, as it is likely that the sustained listening effort experienced by these individuals has a greater influence on fatigue and speech comprehension.

In conclusion, the experiments on listening demand provided partial support for the hypotheses that listening effort (operationalised as PNS withdrawal and SNS activation) should increase as a function of listening demand while comprehension is possible. Evidence for SNS myocardial activation as a function of demand was found. Yet, no evidence supported the theorisation that PNS withdrawal is also involved in effortful listening. The results are supportive of Wright's (1996) active coping hypothesis and aid the understanding of the factors influencing effort investment in listening.

1.2. The impact of success importance on effort-driven myocardial activity

MIT predicts that when task demand is unknown individuals use the importance of task success to determine the amount of effort justified for the task. It was predicted that when listening demand is unclear, listening effort (quantified as PNS withdrawal and SNS activation) is a direct function of the importance of success (or the level of potential motivation), manipulated by the amount of monetary reward available for successful speech comprehension.

1.2. I. Experiment 3. The first experiment conducted to test this hypothesis involved a listening task with an unclear demand, which participants completed over four reward levels. As in the two previous experiments, RSA did not respond as predicted, suggesting that PNS withdrawal does not occur as a function of reward in effortful listening. Based on this and previous experimental findings in this thesis, one might assume that PNS withdrawal is not an essential component of effort-driven myocardial activity during listening. Yet, findings from alternative measures of cardiac activity employed in this experiment provide evidence for the effect of reward on listening effort (quantified as SNS activation), when listening demand is unclear. Seemingly, PEP responds reliably to manipulations of factors that alter an individual's motivation to invest listening effort.

Increases in subjective fatigue and effort were hypothesised to increase alongside autonomic activation during rewarded listening. Partial support was found for this hypothesis in that subjective listening effort ratings significantly increased as a function of reward. However, there were no accompanying changes in fatigue. Some researchers have suggested that reward alters motivation for a task in that it can increase the effort one is willing to invest, and counteract the feeling of fatigue (J. Hopstaken, 2016; Hornsby & Kipp, 2016). Nevertheless, response latency did become slower as a function of reward; which some researchers interpret as an indicator of objective fatigue (Hockey, 1997; Hornsby, 2013). Participants were potentially more motivated to select the correct answer in the more rewarding tasks, causing them to take increased care, and thus time, in clicking on the right response. In addition, there appeared to be no evidence for any consistent relationship between variations in myocardial reactivity and subjective ratings of either effort or fatigue, or speech comprehension. However, there was evidence for a relationship between variations in subjective effort and subjective fatigue, which became stronger with increased reward incentive (or success importance). Within each condition, the higher the participants' subjective effort, the higher their fatigue ratings; this finding is consistent with the idea that effortful listening leads to subjective fatigue as reported by hearing-impaired individuals (Alhanbali et al., 2017; Kramer et al., 2006). Research finds that some individuals are less motivated by reward than others, for example individuals with depressive symptoms (Brinkmann & Franzen, 2013). It is equally possible that some participants in this study did not place high value on shopping vouchers, and were thus less likely to invest listening effort to earn the reward. A large variation in individual differences in the appraisal of certain rewards may explain why there was no significant effect of reward condition on effort or fatigue. However, when considering each reward condition individually, the relationship between subjective effort and fatigue emerges, suggesting that individuals who rated high subjective effort were more likely to experience subjective fatigue.

Increased motivation for listening when rewarded indicated by the changes in both subjective effort and SNS-related effort, was not reflected in any improvements in listening performance. A similar finding was highlighted in other research on listening effort during rewarded listening tasks (Koelewijn et al., 2018). It is noteworthy that listening performance in the no reward task was just shy of 80% successful comprehension, indicating that participants were somewhat motivated in an unclear demand task that offered no incentive. MIT predicts that effort is a direct function of success importance in tasks with unclear demand, so this finding is not necessarily in line with this. It is possible that performance was driven by differences in trial-by-trial listening demand, rather than the whole task condition. Indicating that this may be an interaction effect between difficult listening demand and reward, rather than a pure reward effect. Alternatively, other factors influencing success importance may have increased motivation to invest effort in the listening task without a reward, such as personality (Richter et al., 2012; Roets, Van Hiel, Cornelis, & Soetens, 2008). Furthermore, it is possible that the task was too easy, and participants learnt this regardless of unclear or clear group assignment. If this were true reward would not have an effect on effort investment; as success importance is only the limiting factor on the effort-demand relationship.

1.2. II. Experiment 4. This study compared effort investment in a clearly easy listening task to the same task when demand was framed as unclear. According to MIT, individuals should only invest the effort required for task success when difficulty is clear, regardless of reward. However, when demand is unknown, effort should be a function of success importance. It was thus predicted that effort would be low in the clear demand listening task independent of reward level (£1 vs. £9). Whereas, in the unclear demand task, listening effort should be low in the low reward task, but high in the high reward task. So, listening effort was predicted to be highest in the high reward- unclear demand task compared to the other three conditions.

Although the data did not support this specific prediction, listening effort driven SNS activity (indexed by PEP) was unchanged by reward in the clear listening task. However, in the unclear task, PEP decreased to the same level as in the clear tasks, in the unclear demand- high reward condition only. In the unclear demand- low reward task, PEP was decreased compared to the other three conditions. HR also displayed this pattern. It is possible that in the clear demand listening task, the required amount of effort-driven SNS activity was utilised to attain the 90% performance standard. However, when the listening demand was unclear, only the presence of a high reward increased the importance of success enough to warrant this amount of listening effort. In this case, these data provide support for MIT, in that listening effort occurred as a function of demand while listening demand was clear, but as a function of reward when listening demand was unclear.

In combination, the findings from experiments 3 and 4 provide empirical evidence for the impact of reward on effort-driven SNS myocardial activity during listening. These data highlight the importance of a holistic theory-driven perspective when it comes to effortful listening. It is important, in future research, to consider a multitude of motivational factors that might affect effort investment in listening aside from objective listening demand.

1.3. Impact of the listening demand-reward interaction on effort-driven myocardial activity

The final experiment aimed to combine the findings from the two previous studies. Consistent with MIT, listening effort (quantified by PNS withdrawal and SNS activation) should increase as a direct function of listening demand while success is both possible and the required effort is justified. The importance of success (reward) should limit the effort-demand relationship in listening tasks. In all previous experiments, there was no evidence to suggest that PNS withdrawal (quantified as RSA) occurs in conjunction with SNS activation during effortful listening. However, this final study attempted to control for any respiratory variation influencing RSA that may have been overlooked in previous experiments, in a final attempt to quantify the contributions of the ANS branches to cardiac regulation during effortful listening.

However, in this study there was no evidence for the predicted pattern of either PNS withdrawal or SNS activation in response to the listening demand- reward interaction. With regard to SNS activation, this finding is inconsistent with the three previous experiments in this thesis. However, measures of cardiac activity SBP, HR and DBP demonstrated the predicted pattern of reactivity as a function of listening demand, when success was both possible and the required effort was justified. As discussed before, SBP was used regularly in the past to quantify beta-adrenergic myocardial activity (Wright et al., 1986) before PEP gained popularity in MIT research. Some studies have also used HR and DBP to indicate effort-related cardiac activity as a function of the demand-reward interaction (Eubanks et al., 2002). Subjective effort also reflected the predicted pattern. As in previous studies in this thesis, both demand and reward seem to reliably influence participant's perceptions of effort. As in other studies, the correlations between objective and subjective measures appeared to be inconsistent (in experiments 1-4 of this thesis, and Mackersie & Cones, 2011).

In conclusion, this study provided some evidence for the impact of the listening demand-reward interaction on myocardial activity, specifically blood pressure and heart rate. Yet, these data do not provide compelling evidence for the relative contributions of the branches of the ANS to myocardial regulation during effortful listening. Yet, the findings promote an inclusive and systematic approach to listening effort research, including effort-related theories and models of physiology.

2. Theoretical Implications

2.1. The Physiology of Listening Effort

The majority of studies within this thesis provide support for the predictions of MIT, and are specifically in line with Wright's (1996) active coping hypothesis. Overall, beta-adrenergic sympathetic myocardial activity (listening effort) increased as a function of clear listening demand while successful comprehension was possible and the required effort was justified. Furthermore, in unclear tasks, beta-adrenergic sympathetic myocardial activity (listening effort) increased as a function of the importance of successful speech comprehension. These data also suggest that effortful listening is characterised by an uncoupled sympathetic activation mode of autonomic control (Berntson et al., 1991). The lack of evidence that PNS withdrawal accompanies SNS activation in effortful listening suggests that the pattern of autonomic activity during mental effort (specifically listening) is different to that which is required for effortful physical activity (White & Raven, 2014). This provides evidence against the perspective that ANS activity observed during the performance of demanding tasks reflects responses that were once adaptive in ancestral physical situations (Boyce & Ellis, 2005).

It is highly probable that PNS withdrawal is not an essential component of myocardial activation during effortful listening. Many other studies found similar inconsistent findings concerning PNS reactivity and listening effort (Mackersie & Cones, 2011; Mackersie et al., 2015; Seeman & Sims, 2015). However, other studies on mental effort have considered PNS withdrawal to be a key element of myocardial regulation during cognitive effort (Fairclough & Venables, 2006; Fairclough et al., 2005; Porges, 1995). It is thus interesting to consider the possible differences between studies that utilised cognitive-based tasks (i.e. *n*-back tasks) to manipulate mental demand and studies on listening effort. It is conceivable that the effort required, and thus the accompanying myocardial activation, is rather different for cognitive effort and listening effort. The comprehension of speech may occur, to an extent, unconsciously or involuntarily, for example, the ability to overhear conversations that one is not specifically concentrating on. Therefore, due to a level of familiarity with listening in adverse conditions and years of practice with regard to speech perception, listening effort may manifest differently to effort that is required for cognitive tasks that are not frequently engaged with in daily life. Relatedly, the characteristics of the auditory tasks used within this thesis may have contributed to the absence of the effects of listening demand, or success importance, on RSA; meaning that parasympathetic reactivity was not captured by the task. It is of course possible that listening tasks in the laboratory induce effort differently to listening in daily life. Daily life listening is highly stressful (Kramer et al., 2006; Nachtegaal et al., 2009), and also encompasses many social factors that likely add to this. Listening is required for communication and social interaction, which is imperative to life, individuals with hearing-impairment likely feel embarrassment when they are not able communicate with their peers. Whereas, no sure pressures exist in the listening tasks employed in this study. A future task which incorporates conversation, or communication may be better able to bridge the gap between speech perception in the laboratory and real-world communication. Alternatively, a task which gives rise to increased stress might better reflect real world listening effort. The existing listening tasks could be combined with feedback monitoring against peers' average scores, to elicit stress in the participants if they are not performing at the standard of their peers.

It is of note that none of the experiments controlled for medications that might have an impact on cardiovascular measures. Medications such as selective serotonin reuptake inhibitors and particularly beta-blockers can impact on heart rate (Berntson et al., 1997; Grossman & Taylor, 2007; Hintsanen et al., 2007), and cardiovascular parameters measured within these experiments. Future studies should certainly take this limitation into account and control for these extraneous variables.

2.2. Objective vs. Subjective Indicators of Listening Effort

As in numerous studies on listening effort, the experiments within this thesis found that objective and subjective measures of effortful listening are not commonly related (for examples of these inconsistencies see: Desjardins & Doherty, 2013; Gosselin & Gagné, 2011; Hicks & Tharpe, 2002; Larsby, Hällgren, Lyxell, & Arlinger, 2005; Mackersie & Cones, 2011; Mackersie et al., 2015; Zekveld, Kramer, & Festen, 2010). There are multitudes of reasons for this disparity such as individual differences in introspective ability that reduce listeners awareness of changes in mental effort (Picou, Moore, & Ricketts, 2017). Another interesting explanation is the possibility that individuals unintentionally answer a version of the question that is easier to resolve than answering the true question. Participants might reduce the level of complex decision-making required to answer the question by reducing the amount of reflected-on information, for example by cognitively replacing a question about the amount of effort invested with one that asks about task performance (Moore & Picou, 2018). This explanation would offer insight into why participants in Experiment 2 continued to rate their effort to be high in an impossible listening task where performance was poor. The question is if an individual *feels* effort, then are they experiencing effort regardless of the behavioural or physiological indicators? Subjective reports may be highly important as the experience of effort in the hearing-impaired population was first identified by such reports from these individuals (Kramer et al., 2006). They may provide a direct insight into the mental state of the individual in a non-invasive, inexpensive and easily administered way (Moore & Picou, 2018). It is possible that the uncorrelated subjective and objective measures occur because subjective reports are susceptible to different parameters than behavioural or physiological measures. Understanding which of these measures are more related to both speech comprehension performance and hearing fatigue could provide valuable additions to the collaboration of hearing aids to reduce effort and fatigue. In these studies, although physiological effort was, overall, reliably indicated by SNS-driven myocardial activity, subjective effort was more consistently related to subjective fatigue than was physiological effort.

2.2. I. A Note on Indicators of Hearing Fatigue. Much of the initial research on effort in listening suggested that the sustained effort endured by hearing impaired individuals causes them to experience hearing-related fatigue that has consequences for well-being. Therefore, understanding how hearing fatigue manifests in relation to effortful listening warrants research. These experiments looked at the relationship between objective (performance decrement) and subjective fatigue, and both objective and subjective measures of effort. However, the data was typically inconsistent; existing literature also observed these discrepancies. For example, if hearing fatigue results from increased effort, one would expect that the degree of hearing loss, which likely determines the amount of effort required to interpret speech, should relate to the degree of experienced fatigue. Yet, researchers have found contradicting evidence with some studies suggesting that these factors are related but others suggest they are not (Alhanbali et al., 2017; Nachtegaal et al., 2009).

2.2. I. a. Limitations in Quantifying Fatigue. There are many reasons as to why a clear relationship between effort and fatigue is not easy to identify. One of these may be due to ambiguity in the measurement of fatigue; research finds that objective and subjective measures of fatigue often convey different results (Hornsby et al., 2016). Interpreting performance decrements as objective fatigue may be problematic. Decrements are assumed to be caused by the effects of increased task demand on resultant effort, causing individuals to falter on efficiency in order to maintain overall task performance. Yet, this decrement could also indicate complete withdrawal of effort and thus theoretically would not constitute effort-related fatigue but task disengagement. Furthermore, decrements can arise from boredom that can occur during easy tasks in the absence of effort (Hockey, 2011). Similarly, problems with the interpretation of questionnaires, response bias and introspection pose problems for the quantification of subjective fatigue.

Research efforts into the relationship between listening effort and hearing fatigue might be best focused on the hearing-impaired population in the real world. Sustained effortful listening experienced by these persons is likely to have a greater influence on fatigue and speech comprehension than short-term lab-based effortful listening. Furthermore, it is possible that the hearing-impaired population experience a circular effect of effort and fatigue. These individuals need to invest effort in daily life to cope with increased demands, leading them to feel fatigued. Then, the presence of chronic hearing fatigue impacts on their ability to invest listening effort. It is imperative to help to reduce effortful listening in the population to combat this cycle.

3. Thesis Limitations

This thesis used a theory of effort investment, MIT, to guide experiments focused on myocardial quantification of effortful listening and its potential relationship to subjective effort, fatigue and speech comprehension. The relative contributions of the ANS branches to the regulation of CV reactivity during effortful listening was a main of this research. The measure of SNS-driven myocardial activity was highly controlled, ensuring that changes in PEP could be accurately interpreted as SNS activation. However, in the early experiments, there were methodical flaws that may have hindered the quantification of PNS reactivity. RSA is influenced by respiration rate, which is not under parasympathetic control, the first four studies in this thesis failed to control for this variable and thus the measure of RSA is not a completely accurate measure of PNS reactivity (Grossman, 2004). Furthermore, there are variables that might have influenced the autonomic arousal of the participants, such as caffeine consumption or physical activity prior to testing. Although these factors were partially controlled for through baseline measures and change scores, they might be worth considering in future research. An additional defect may be that the participants in all experiments were tested at various different times of day, ranging from 8:00 to 19:00. The time of day that testing took place could have influenced participants subjective responses, particularly on the fatigue questionnaire (Ferguson et al., 2012). Although fatigue was also calculated as a change score from baseline to control for influences such as these, it may still have affected the magnitude of ratings.

Another limitation to consider is the range of factors that could have influenced the participant’s level of motivation to invest effort in the experimental tasks. Although this research involved a specific investigation into task demand and reward, other factors may have affected the level of effort participants were willing to invest. Such as, goal orientation, the need for cognition (Roets et al., 2008); mood

(Richter & Gendolla, 2009a) or cognitive ability (Zekveld et al., 2011). For example, studies found that listeners correctly perceive speech when the task goal is based on comprehension, but they do not accurately remember it (Brown, 2000; Pichora-Fuller, Schneider, & Daneman, 1995). This suggests that the goals of an individual influences the investment of effort in a given task. Incidentally, it also highlights that objective measures of performance may not reflect the underlying effort involved, as participants will invest less effort to achieve the main goal but falter in other un-measured areas of task performance.

4. Future Research

This thesis highlights the importance of adopting a holistic approach to researching listening effort. The data show that effortful listening (reflected in subjective responses and SNS activation) occurs not only as a function of demand but also motivational factors that affect the importance of success. These experiments focused particularly on the impact of reward as a determinant of success importance. However, there may be other relevant factors that influence effortful listening that would be interesting to consider in future research, such as goal orientation, fatigue, and personality factors. Understanding the various influencers of potential motivation in effortful listening would help paint a more complete picture of the factors that both encourage and discourage effort investment in listening.

A main aspiration for future research is a shift towards a focus on a clinical population of listeners with complex auditory impairments. Since the experiments in this thesis provided valuable information about the correlates of listening effort, specifically myocardial SNS activation and subjective effort, it would be beneficial to see if these are also present in the hearing-impaired population. Furthermore, the difference in effort experienced by hearing-impaired individuals may be essential for understanding the relationship between the myocardial indicators of effort, subjective effort and the manifestation of hearing fatigue and their impact on speech comprehension.

Finally, future research focusing on the incorporation of validated measures of listening effort into hearing aid calibration might be able to improve the quality of life for the hearing-impaired population. If audiologists can identify the level of effort that is required for listening when a patient is wearing a hearing aid, it might be possible to alter the calibration to reduce this effort. In doing so, audiologists may be able to improve hearing aid adherence and importantly reduce effort-related fatigue and subsequent effects on wellbeing.

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Appendices

Appendix 1. Experiment 1 Fatigue Questionnaire Items

This novel fatigue questionnaire was devised specifically for use in the first experiment of this thesis. Participants responded to the six items using a 5-point Likert Scale where 1 represented “much less than usual” and 5 represented “much more than usual”.

1. How fatigued do you feel right now?
2. How worn out are you currently?
3. At present, how tired are you feeling?
4. Are you feeling energetic at the moment?
5. At this time, do you feel well rested?
6. How lively do you currently feel?

Appendix 2. Experiment 2-5 Fatigue Questionnaire Items

This novel fatigue questionnaire was created specifically for use in the second, third, fourth and fifth experiments of this thesis. Participants selected a word from two on screen options that most accurately described how they were feeling at that moment.

1. Tired / Well-rested
2. Tired / Lively
3. Tired / Energised
4. Worn out / Well-rested
5. Worn out / Lively
6. Worn out / Energised
7. Fatigued / Well-rested
8. Fatigued / Lively
9. Fatigued / Energised

Appendix 3. Table listing examples of the speech stimuli used in the SiWN tasks

Table 14.

Four examples of the speech stimuli and comprehension questions of the SiWN task (and its variants, SiWN-Easy and SiWN-U) employed in Experiments 2, 3, 4 and 5.

Stimuli	Liverpool women's netball club go on a social outing every week, after practicing at the sports centre. This week, the women walked to the station on Friday. They bought three cups of fresh coffee and talked about improving their team strategy for the next game. They considered holding try outs for new team members to improve their capability.
Question	Where did the women go?
Response Options	Station / Café / Canteen
Stimuli	Rob works at a garage during the week. He likes his job a lot, but he wishes he had a more physically active role. To try to keep fit, he cycles to work every day. He enjoys it because he rides down the scenic canal path. On Wednesday, Rob decided to sign up for a 5-mile triathlon to encourage himself to cycle more, and to spend more time outdoors.
Question	Where does Rob work?
Response Options	Garage / Garden Centre / Golf Course

Stimuli	The Old Ship Pub sold all their packets of crisps on Saturday, which is the busiest day of the week. So, the head barman decided to run over to the local shop to find some. When he arrived, he bought the last six packets on the shelf. He was worried that it was not enough for all the customers, so he ran to the bigger supermarket to buy more.
Question	What did the pub run out of?
Response Options	Crisps / Chips / Cakes
Stimuli	Jack regularly competes in marathons for his local charity. He runs to the shop every weekday morning, to try to improve his running speed. This week, when he arrived at the shop, he bought six brown eggs. Then he admired at the sweets next to the counter. He wished he could buy them too, but he can only eat healthy food before he competes in the marathon.
Question	What did he buy?
Response Options	Eggs / Bags / Pegs