Emotional physiological synchrony and its relation with cognitive performance

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Objectives
The purpose of this thesis is to study physiological connections during emotion, and investigate whether emotional synchrony predicts cognitive performance. It is widely acknowledged emotions affect human behavior extensively, however, less is known about how different processes of emotional regulation are related. These relations can be studied by measuring emotional physiological synchrony, determined as the index value of similarities between physiological processes that are recorded while experiencing emotion. When people experience emotions, activity of bodily functions changes, and the synchrony measure is meant to reflect whether the changes vary in the same manner. Multiple different methods for determining the emotional synchrony have been suggested, yet there is no established practice. In this thesis, a new method for determining emotional physiological synchrony is presented. Also, cognitive performance is measured to understand whether synchrony has a relationship with behavioral outcomes. The research question of this thesis is: Does synchrony of emotional responses predict cognitive performance?

Methods
32 subjects participated in the experiment in which three signals—electrodermal activity (EDA), electroencephalography (EEG) and facial electromyography (fEMG)—were recorded while subjects' performed in cognitively loading and emotionally arousing tasks. Cognitive performance was measured by Visual Search and Mental Arithmetic tasks. Emotional synchrony was determined based on each subjects' physiological activity during Mental Imagery task, in which subjects recalled their emotional memories. A new method for determining the synchrony was created, consisting of two approaches: Approach 1 for investigating the synchrony of physiological responses over time, within one emotion, and Approach 2 investigating synchrony of physiological responses between two emotions, averaged over time. Both approaches employed Kendall correlation and cosine similarity analysis. The physiological responses extracted from the signals included: skin conductance response (SCR) from EDA, frontal alpha asymmetry (FASYM) from EEG, and corrugator supercilii (CRG), zygomaticus major (ZYG) and orbicularis oculi (ORB) from fEMG. The relationship between synchrony indices and cognitive performance was explored with linear models.

Results
It was found that strong synchronization between facial muscles ZYG and ORB corresponded to the positiveness of emotions having greatest activation during highly arousing positive emotions: enthusiasm, joy and triumph. This synchrony was linked with increased performance in Visual Search tasks, indicating that subjects whose facial muscle activation synchronized during Mental Imagery, tended to achieve better performance scores in Visual Search.

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Tiivistelmä – Referat – Abstract

Tavoitteet
Tämän opinnäytetyön tarkoituksena on tutkia emootioiden aikana tapahtuvien fysiologisten prosessien vuorovaikutusta, sekä niiden mahdollista yhteyttä kognitiiviseen suoriutumiseen. Emootioilla tiedetään olevan selkeä vaikutus ihmisten käyttäytymiseen, mutta siitä miten samanaikaiset, emootioiden säätelyyn liittyvät fysiologiset prosessit suhteutuvat toisiinsa, tiedetään vähemmän. Näiden yhteyksien vuorovaikutusta voidaan tutkia määrittelemällä fysiologisen synkronian mittari, joka kuvastaa erilaisten emotionaalisten signaalien samankaltaisuuksia. Ihmisten fysiologiassa tapahtuu muutoksia emootioita koettaessa, ja synkroniamittarin onkin tarkoitus kuvastaa kuinka yhdenmukaisia nämä muutokset ovat. Vaikka erilaisia tapoja synkronian määrittelyyn on esitetty, yhtä vakiintunutta tapaa ei toistaiseksi ole. Tässä opinnäytetyössä kehitetään uusi metodi fysiologisen synkronian määrittelyyn. Tutkimuksessa on myös mitattu kognitiivisen suoriutumisen tasoa, jotta voidaan tutkia, onko alttiudella kokea emotionaalista synkroniaa yhteyttä käyttäytymisen kanssa. Tässä opinnäytetyössä etsitään vastausta tutkimuskysymykseen: Ennustaako emotionaalisten vasteiden synkronoituminen kognitiivista suoriutumista?

Metodit
32 koehenkilöä osallistui tutkimukseen, jonka aikana nauhoitettiin kolmea fysiologista signaalia — ihon sähkönjohtavuutta (EDA), aivosähkökäyrää (EEG), sekä kasvojen lihassähkökäyrää (fEMG) — samalla kun koehenkilöt suorittivat kognitiivisesti kuormittavia sekä emotionaalisesti aktivoivia tehtäviä. Kognitiivista suoriutumista mitattiin käyttämällä visuaalisen haun tehtäviä sekä päässälaskutehtäviä. Emotionaalinen synkronia määriteltiin koehenkilöiden fysiologisten aktivaation perusteella, jota nauhoitetiin samalla kun koehenkilöt ajattelivat heidän omia emotionaalisia muistojaan. Uusi metodi emotionaalisen synkronian määrittelyyn sisältää kaksi eri menetelmää. Ensimmäisessä menetelmässä tutkittiin fysiologisen synkronian ilmenemistä yhden emootion sisällä ja toisessa menetelmässä tutkittiin fysiologisen synkronian ilmenemistä kahden eri emootion välillä. Molemmat menetelmät pohjautuivat Kendall-korrelaatioon sekä kosini-samankaltaisuuteen. Fysiologiset indikaattorit, joita signaaleista tutkittiin, koostuivat ihon sähkönjohtavuuden vasteista (SCR), etuotsalohkolla ilmeneen alpha-taajuuskaistan epäsymmetrian suureesta (FASYM), sekä kasvojen lihaksista kulmakarvojen rypistäjälihaksen (CRG), poskipäälihaksen (ZYG), sekä silmän kehälihaksen vasteista (ORB). Synkronian ja kognitiivisen suoriutumisen välistä yhteyttä tutkittiin lineaarisilla malleilla.

Tulokset
Tulokset osoittivat, että kasvojen poskipäälihaksen ja silmän kehälihaksen vasteet synkronoituivat voimakkaasti ollen suoraan verrannollisia koettujen emootioiden positiivisuuden kanssa. Tämän synkronian ilmeneminen oli yhteydessä parempaan suoriutumiseen visuaalisen haun tehtävissä, viitaten siihen että niillä koehenkilöillä joiden kasvojen lihasten vasteet synkronoituivat emootioiden kokemisen aikana, ilmeni myös taipumus suoriutua paremmin visuaalisen haun tehtävissä.

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Contents

1 Introduction

The way people experience, interpret and are influenced by emotions, varies extensively between individuals. Despite decades of research into emotions, their construction from neural level to behavioral consequences is still debated. Issues such as numerous competing theories of emotions (Bradley and Lang, 2007), and disagreements regarding the fundamental questions of emotion (Barrett, 2006) might explain why such debates persist.

Theories of emotion are often divided into dimensional and discrete models of emotion. These models are seen as competing, yet, as Harmon-Jones et al. (2017) notes, both perspectives on emotions' construction give insights to the psychology of emotions. Instead of contrasting various theories of emotion, Harmon-Jones et al. (2017) argue it is more relevant to focus on creating evidence that integrates theoretical perspectives.

In the field of emotion research, physiological synchrony has gathered increasing interest. Research on physiological synchrony examines the connections between different bodily functions and their tendency to align. The ways of determining the connection metrics vary depending on the purpose of the research. Also, the ways of naming of the connection metrics vary, for example synchrony and coupling can be used as synonyms.

However, despite different terminologies and definitions, research of physiological synchrony aims at producing new evidence on relationships between different physiological and/or neural functions, each function having a role in emotion regulation, and to learn more about the mechanisms underlying emotional experiences.

Studies have so far emphasized inter-individual synchrony while paying less attention to intra-individual synchrony. Only some studies have investigated connections between different physiological processes within a body (e.g. Kettunen et al., 1998; Bradley et al., 2010; Kelava et al., 2015).

In this thesis, physiological activity of emotions is investigated by using Mental Imagery task in which subjects recalled their own emotional memories. Nine emotions were included: anger, depression, disgust, empathy, enthusiasm, fear, joy, relaxation and triumph. A new method for investigating emotional synchrony is created based on the emotional activity, and its relationship to performance in Visual Search and Mental Arithmetic tasks is investigated. More specifically, it is examined whether individuals of different levels of physiological responsiveness benefit or suffer from their natural physiological reactivity tendency. The main research question of this thesis is: Does synchrony of emotional responses predict cognitive performance?

To investigate the physiological activation from emotion eliciting conditions, three signals are compared: electroencephalography (EEG), electrodermal activity (EDA) and facial electromyography (fEMG). In studies of emotion, these signals are considered as a temporally precise and reliable indicators of emotional experience within the body. In order to compare the patterns of physiological activation over time, a new method is created. The method includes two different approaches, Approach 1 investigating the similarity of physiological responses over time, within one emotion. Approach 2 investigating similarity of physiological responses between two emotions, averaged over time. Here, similarity of responses is conceptualized as a synchronization of the signals.

There are two key findings of the study: First, high synchronization of facial muscle activation corresponds to the positiveness of the emotions being present during highly arousing positive emotions—enthusiasm, joy and triumph. Second, this synchrony is linked with increased performance in Visual Search tasks.

1.1 Definition of emotion

Research on emotions focuses on studying humans' emotional experiences that can be understood as described feelings, physiological reactions, or neural states, and how they relate to a wide variety of internal factors and external stimuli. Following this wide range of approaches into studying emotions, there is no commonly accepted definition for emotions despite their shared intention of understanding emotions.

Emotional experiences are often described using words emotion, mood, or affect. Although closely related, emotion and mood are generally agreed to be a distinct phenomena (Beedie et al., 2005). Mood and affect are often used interchangeably.

Ekman (1992) describes factors that are unique for emotion and separate them from other affective processes: rapid onset, short duration, they are automatically evaluated and have coherent behavioral responses. Affect is a neuropsychological state that described to be always present, having many causes, and to be a consciously accessible process of pleasure and activation (Russell and Barrett, 1999). Thus, affect is a longer and less intensive experience than emotion.

Emotions are often divided into two different categories: primary and secondary emotions. Primary emotions, also called as basic emotions, are considered to be an evolutionary mechanism for aligning bodily systems and enabling survival under changing circumstances. Primary emotions are often thought to have a signature neural circuits and physiological responses (e.g. Ekman, 1992; Panksepp, 1982), although this view has been lately challenged (e.g. Barrett, 2017). Primary emotions are defined to include: anger, disgust, fear, happiness/joy, depression/sadness, surprise. Definitions of the neural and physiological activity patterns of secondary emotions are less clear and their relationship to primary emotions remain unsolved (Ekman, 1999). Examples of secondary emotions could be: shame, longing, guilt, love (Saarimäki et al., 2018), triumph, enthusiasm (Shaver et al., 1987), relaxation and empathy (Cambria et al., 2012). They are suggested to built on primary emotions, being more of a mixture of several emotional states involving conscious interpretation of a situation (Ekman, 1999). Also, it has been proposed that cognitive representations of secondary emotions are influenced by cultural aspects such as learning and social norms (Panksepp and Watt, 2011).

Already long ago it was recognized that intensity of emotional experience varies extensively between individuals (e.g. Diener et al., 1985; Larsen and Diener, 1985). At one end of the continuum are stable emotional experiences causing only minor fluctuations, and at the other end are located intensive, strong experiences, indicating higher emotional reactivity (Larsen and Diener, 1987). Therefore, individuals with the tendency of higher reactivity experience that the same emotional stimuli cause more emotional activity than happens for individuals of lower reactivity, regardless of the valence of the emotion. Differences of emotional reactivity relate to cognitive and affective processes, and also have an influence on behavior (Larsen and Diener, 1987).

Emotional experiences are often considered to be conscious interpretations of a given situation, and can be investigated by self-reports (Frijda, 2009). However, self-reports are criticized for their unreliability, and it is possible that the inconsistent use of different emotion words biases the results (Frijda, 2009). Also, individuals tend to conceptualize emotions differently (Barrett, 2017). For example, the interpretation and behavioral outcomes of the emotion anger may differ between two individuals.

Emotions also activate bodies in unconscious ways. According to Frijda (2009), emotional experience can be described as the reflection of motivational, cognitive, behavioral, perceptual, and peripheral-physiological components whose combination occurs in consciousness even though the individual components themselves are not conscious. Because of this variety in activation, self-reports do not sufficiently capture the range of emotional experience.

1.2 Dimensional emotion theory

Several different theories concerning the neurophysiological, psychological, and behavioral consequences of emotions have been suggested. One of the most prevalent theories is called dimensional emotion theory, that suggests a person is in some emotional state at all times, and the extent of the state varies among a dimensionality of emotions. Emotions can either be modelled within a three-dimensional space consisting of varying amounts of pleasure, arousal and dominance (Russell and Mehrabian, 1977) or with a two dimension model consisting of arousal and valence (Russell, 1980). For example, fear would be a state of negative valence and high arousal while depression would be a state of negative valence and low arousal. Thus, emotions are co-dependent and vary in volumes. For instance, increased amount of dominance distinguishes anger from anxiety, or surprised from alertness (Russell and Mehrabian, 1977).

However, even though different dimensional models share the ideology that emotions are constructed from varying amounts of valence and arousal (and dominance, in some theories), the model's behavioral and interpretative implications are inconsistent. Lang et al. (1998) and Cacioppo et al. (1999) suggest that affective valence is tightly associated with motivational direction, meaning that positive affect is linked with approach motivation and negative affect with avoidance motivation (Harmon-Jones et al., 2017). Arousal has been suggested to reflect the amount of motivational intensity of a given situation (Lang et al., 1998) which seems to be an overly simplified claim based on more recent studies. Gable and Harmon-Jones (2013) showed that intensity of arousal was not equal to the amount of approach behavior. Thus, it is likely that there is a correlation between arousal and motivational intensity but the two do not seem equivalent: for instance, it is possible to be aroused while watching a funny video clip but at the same time feel unmotivated by it (Harmon-Jones et al., 2017).

Barrett (2017) even argues that how emotions are felt depends on circumstance: while different physiological responses naturally occur in the same emotion category, there is no specific fingerprint for any emotion, but rather the situational cues determine how reactions caused by those physiological responses are interpreted. For example, there are general physiological responses to anger, but even when controlling for the individual and the environment, responses of anger can vary across time.

Therefore, different dimensional theories contradict, and none of the models has received full support from the scientific community. However, all dimensional models are grounded on the idea that emotions are composed of altering and changing physiological responses which determine the emotion. And so far, that seems to the most complete and supported view of describing the complexity of emotion, even though the specifics differ between the models.

In this thesis emotions are viewed as dimensional theory suggests. Emotions that are included in the experiment, are placed to the two-dimensional space according the model, as Figure 1 shows.

1.3 Emotions and performance

One way to examine emotions' behavioral outcomes is to investigate their relationship to performance. Measures of performance vary between the studies, but the key idea is to investigate whether negative or positive affects or emotions are associated

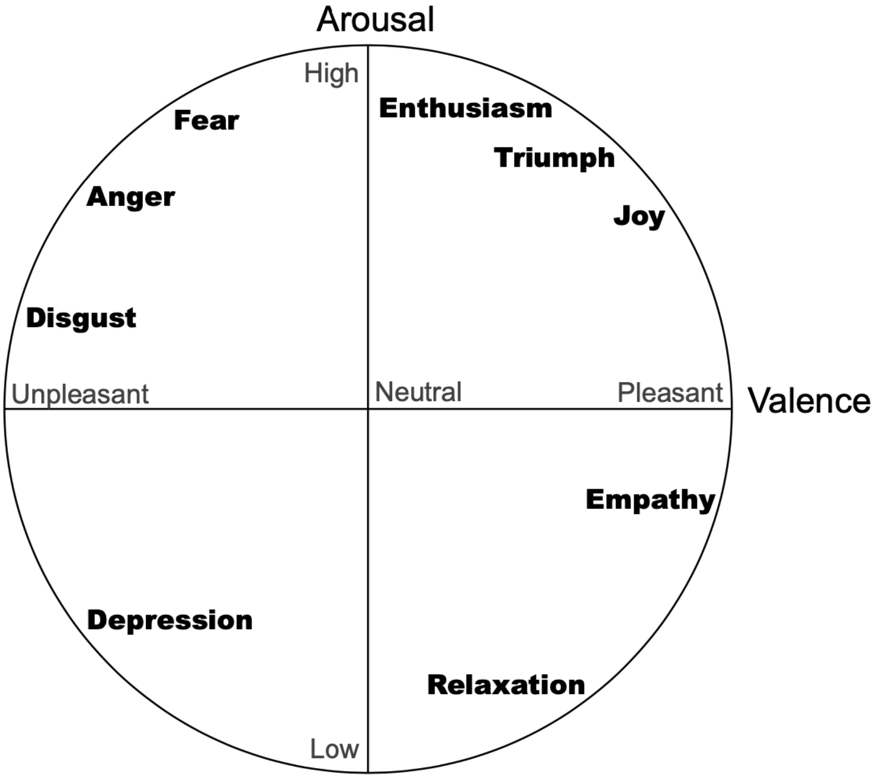

Figure 1: Primary and secondary emotions classified according the two-dimensional theory (see Russell 1980). Arousal is presented on the vertical axis, varying from low to high, and valence is on the horizontal axis, varying from unpleasant to pleasant.

with a level of performance. For example, already Eysenck (1985) reported that anxiety decreased the ability to store information to working memory and utilize it, and Ashby et al. (1999) suggested that even a slight increase in subjects' dopamine levels induced through positive affect (i.e. by reporting that subject accomplished a difficult task successfully) enhanced cognitive performance, such as working memory or creative problem solving. In a more recent study, Nadler et al. (2010) investigated how moods induced before a learning task affected learning performance, finding subjects in the positive-mood condition performed better and their learning was enhanced compared to groups of neutral and negative mood. Also, subjects of positive mood group showed higher cognitive flexibility by finding an optimal strategy in the early phase of task (Nadler et al., 2010).

Because emotions activate individuals differently, the link between emotions and behavior is ambiguous. Emotions modulate components of cognitive control (Gray, 2001) and they are also known to affect and mediate behavior by altering attention, memory, perception and psychological processes (Barrett, 2006) which influence performance through behavior. For example, Gray (2001) investigated differences in spatial and verbal performance. They found that in situations of emotional withdrawal, performance on task types that demanded spatial perception was enhanced whereas performance on tasks of verbal processing was impaired. Correspondingly, in approach-inducing emotional states, performance was enhanced in verbal processing and impaired in spatial perception tasks (Gray, 2001). In another study, in situations where emotions increased the amount of information processed, emotional experiences were shown to capture attentive resources away from task-oriented processing, resulting in decreased task performance (Meinhardt and Pekrun, 2003).

General mood states have also been shown to affect problem solving ability. According to Clore and Huntsinger (2007, 2009) positive mood increases creativity during problem solving tasks, and negative mood induces more rigid and analytical processing. However, emotional valence alone does not determine emotions' effect on performance. As emotions differ by the amount of activation they arouse, deactivating negative emotions (such as boredom and hopelessness) might have different impact on performance compared to activating negative emotions (such as anxiety, anger and shame). Yet, emotions are not simply activating or deactivating: they respond to context. Depending on circumstances, anxiety might cause behavioral freezing and while freezing obviously decreases performance, anxiety can sometimes improve performance through increased motivation (Pekrun et al., 2002).

Overall, findings on how emotions affect performance are ambiguous. Emotions clearly impact individuals differently and changing circumstances affect emotional experience. As Pekrun and Stephens (2009) described, the overall effect of any given emotion on performance is likely to be a combination of the mechanisms facilitated by the emotion and its interaction with task demands.

1.3.1 Cognitive processes of Mental Arithmetic and Visual Search

Mental Arithmetic is a standard task within psychological studies, and succeeding in it depends on working memory capacity. Working memory, also known as a short-term memory, can be defined as a storage and manipulation unit for information which is no longer available to the senses (Kiyonaga and Egner, 2013). Already Hitch (1978) reported some memory strategies of mental arithmetic task, and determined factors that affect task performance. A common strategy is to break problems into series of smaller problems, although the specific implementation varies significantly among individuals (Hitch, 1978). Errors may happen because initial and temporary information are both stored in the working storage, making them vulnerable for failure (Hitch, 1978). Due to the complex nature of the task, mental arithmetic is often measured in psychophysiological studies to investigate cognitive workload.

Visual Search is also a commonly measured task type. Different variations are used for measuring different visual and attentive processes. For example, Bravo and Nakayama (1992) conducted an experiment with several different task types – they instructed subjects to observe the color, shape, and presence of the odd-colored target. Other circumstances were identical between the task types, except the characteristics of the main target. Even though the visual tasks were different, a general pattern occurred – reaction times for discriminating a subtle feature of the target decreased when the number of distractions increased, but interestingly, reaction times were not affected by the number of distractors when detecting the target or its unique feature. The authors concluded the finding was due to the utilization of altering attentive mechanisms: focal attention in the first case and distributed attention in the other (Bravo and Nakayama, 1992). Therefore, as various visual search tasks employ different attentive mechanisms, it is preferable to investigate these systems by using versatile stimuli.

Attentive processes can be conceptualized by separating them into two categories, external and internal. External attention means perceptual attention, and mechanisms that select and modulate sensory information, while internal attention means internal processes of attention such as long-term or working memory, tasks sets and cognitive control (e.g. Chun et al., 2011). Therefore, working memory is related to attention, and is utilized in situations of attentive processing (Kiyonaga and Egner, 2013).

Internally guided perceptual processes, or endogenous processes, activate brain differently than external, or exogenous processes (Corbetta et al., 2008). Endogenous processes are generated and maintained by a dorsal frontoparietal network. Ventral frontoparietal network responds when relevant objects or targets are detected, and is not involved in task preparation or planning, like dorsal frontoparietal network is. Therefore, endogenous processes show more activation higher in the parietal cortical areas, and exogenous processes slightly lower around temporal areas. Normal perceptual processes demand sufficient interaction of the two networks, and are often activated at the same time, for example when reorienting attention (Corbetta et al., 2008).

While it has been acknowledged that working memory and attention are interrelated processes, the degree of this relationship remains unclear (e.g. Awh et al., 2006). Working memory encoding and visual attention have been shown to cause overlapping activation in frontal and posterior regions, therefore competition of the resources can restrict the overall processing capacity (Mayer et al., 2007). It has also been suggested that working memory and attention are not separate processes, but two sides of the same mechanism, with internal representations reflecting processes that are traditionally thought as working memory, and external representations reflecting processes that are traditionally thought as selective attention (Kiyonaga and Egner, 2013).

The tasks of Visual Search demand more external attention than the tasks of Mental Arithmetic, which are more internally focused. Certainly, the division of the tasks to external and internal is approximate, since both of the tasks types rely heavily on the working memory capacity and utilize also other cognitive processes, such as long-term memory for the arithmetic knowledge or executive functions, but the main characteristics of the tasks are probably different enough to show differences in information processing.

1.4 Psychophysiological measuring of emotions

Psychophysiology can be measured to investigate how intensive the physiological activation related with emotion is. Psychophysiology aims to find connections between physiological processes (such as skin conductance or brain waves) with psychological phenomena (such as emotions), and is considered to be a more temporally precise measure for investigating emotions than self-reports are.

Emotions are often investigated in laboratory settings by using stimuli that is intended to elicit emotional experience, while recording the physiological experience of the subject. Several types of stimuli are used: videos, images, narratives, audio clips, to mention a few. Since emotions are shorter and more intensive experiences than affective states, stimuli are repeated in order to receive enough, and reliable, data of physiological changes that emotions arouse in a body. However, measuring emotions is not without challenges. One concern is the ambiguity of physiological signals, i.e. opposite emotions may cause similar type of bodily activation.

Experiencing emotions can also vary depending on situation (e.g. Barrett, 2017). Therefore studying emotions demands a controlled research setting, where any additional stimuli that may cause changes in subjects' physiology can be ruled out.

Experience of emotions activates the whole body (Nummenmaa et al., 2014), and several commonly measured signals have established their place in emotion research. Signals that are relevant from the scope of emotion research include: electrodermal activity (EDA), electrocardiography (ECG), electroencephalography (EEG), facial electromyography (fEMG), electrooculography (EOG) and respiration.

Psychophysiological measurement starts by attaching the electrodes on the surface of the skin and checking the signal quality. A common procedure is to record baseline for a few minutes before starting the actual experimen, as it is presumed that the physiological state of a subject changes during the measurement, i.e. due to emotionally arousing stimuli. In analysis, baseline activity is used to control for the inter-individual variability of signals.

1.4.1 Electrodermal activity

Electrodermal activity (EDA), also known as sweat gland activity, is an often investigated signal in emotion research, due to its sensitivity to different psychological states (Cacioppo et al., 2000). EDA is investigated by attaching electrodes on the skin for measuring a voltage current between a pair of electrodes (Cacioppo et al., 2000). The flow of the current changes with skin conductance. Activation of the autonomic nervous system produces electrodermal activity, which is caused by the homeostatic thermoregulation of the sympathetic nervous system (Boucsein, 2012). When sweat fills the ducts of the skin, a more conductive path emerges. The higher the sweat rises, the lower is the resistance of the skin, and the altering level of sweat in the ducts changes the signal (Cacioppo et al., 2000). As Boucsein (2012) described, states of higher arousal induce higher electrodermal activity, in which the amount of excreted sweat is higher, which then results in rapidly evolving skin conductance responses (SCR).

SCRs are commonly measured units of electrodermal activity, and they are measured as peak amplitudes thus being the phasic components of the signal. The minimum value criterion for the size of an amplitude is between 0.01-0.05 μS (Cacioppo et al., 2000). The latency of SCR is often between 1-2 seconds after the stimuli (Boucsein, 2012) but might even be lengthened to 5 seconds due to skin cooling (Edelberg, 1967).

Other generally investigated metrics of EDA are the tonic component (tonic level of the skin) as well as latency, habituation and recovery time of SCRs (Cacioppo et al., 2000). However, from a perspective of emotion research, SCR rate and amplitude are convenient metrics for investigating arousal, due to the direct relationship between arousal and number or size of excreted SCRs.

1.4.2 Electroencephalography

Electroencephalography (EEG) is a commonly used brain research method, being a noninvasive measure of electrical potential differences in the neuronal dendrites. EEG is measured by attaching electrodes on the scalp at the standard locations (Rippon, 2006). Acquiring EEG is simple, and it provides an accurate reflection of brain activity with the time resolution of milliseconds. Measurement is most sensitive to brain activation right under the electrode, meaning it can only be used to investigate the activation of place-specific surface structures of the brain (Hari and Puce, 2017).

EEG signal results from current flow of dendrites in the cerebral cortex (Rippon, 2006). Electrodes that are attached on the scalp are called active electrodes. Inactive electrodes known as reference electrodes are also used for comparison between the brain signal and non-brain signals such as electrical noise or muscle activation, and they are attached to earlobes, mastoids or the tip of the nose (Rippon, 2006). By referencing it is possible to subtract the non-brain signal from the brain signal, the resulting signal reflecting the brain activation that is investigated.

Electrical potential differences occur when a neuron activates other neurons through afferent action potentials, resulting in post-synaptic potential. While a post-synaptic potential happens, the membrane of the dendrite depolarizes and becomes more negative than the cell soma (Cacioppo et al., 2000). As a result of the potential difference, electrical current runs from the non-excited cell soma to the excited dendrite, creating negative polarity on the scalp. Conversely, when the cell soma is excited, the electrical current flows to inverse direction (Cacioppo et al., 2000).

Neural oscillations are rhythmically occurring neural activity patterns resulting from the summation of excitatory and inbitory post-synaptic potentials in cortical neurons (Cacioppo et al., 2000). The optimal orientation of cortical neurons allows summation to happen by involving tens of thousands neurons. For oscillatory rhythms to occur, fluent interaction of the neural circuits between the thalamus and the cortex is necessary (Cacioppo et al., 2000).

EEG is used for investigating numerous different brain functions. For example, EEG is often measured in studies of attention, auditory or visual information processing. EEG is also an accurate method for comparing activation between the hemispheres, as it allows investigation of differences in motivational processes that are suggested to be located on different sides of the brain. Some literature suggests that relatively higher left side activation indicates approach motivation and relatively higher right side activation indicates withdrawal motivation (e.g. Coan and Allen, 2003; Adolph et al., 2017).

When EEG is used, the frequency band under investigation is chosen based on the phenomenon that is studied. In this thesis, alpha rhythm is investigated, since alpha activity is often used in studies of attention and brain asymmetry.

Alpha oscillations Alpha rhythm is the neuronal activity within 8-13 Hz power range (Cacioppo et al., 2000). Alpha frequency has inhibitory effect in brain functioning since working memory capacity is limited to approximately four items (Luck and Vogel, 1997). Selecting the most relevant information for further processing and excluding the rest is essential for successful performance. The central role of alpha frequency is to suppress non-relevant attentive processes and the higher the alpha power is, the higher the perceptual threshold is (Foxe and Snyder, 2011). Concentration or sudden alerting can reduce or can even abolish alpha waves (Cacioppo et al., 2000).

Occurrence of alpha waves is inversely related to attention, and a standard procedure to investigate hemispheric differences is to calculate an asymmetry index of the alpha frequency. The asymmetry index is obtained by subtracting the natural logarithm of the left side power value from the natural logarithm of the right side power value (Cacioppo et al., 2000). Therefore, if the resulting index value is negative, more alpha activation is present on the left side, and due to the inverse relationship with brain activation, there is more ongoing processing on the right side.

Previously, it was thought that the differences in brain activation asymmetry would reflect the division of emotional valence to the distinct hemispheres, with increased left side alpha activity reflecting positive feelings and increased right side alpha activity reflecting negative feelings (e.g. Wheeler et al., 1993). However, instead of the emotional valence, further studies have supported increased activation on the left side reflecting approach motivation and increased activation on the right side reflecting withdrawal motivation. For example, anger is known to have negative valence, but as Harmon-Jones and Allen (1998) results suggests, anger activates the left side more than the right side, indicating approach motivation. Other authors have later made similar findings, Hewig et al. (2004) by investigating anterior alpha asymmetry and Gable and Poole (2014) by investigating frontal alpha asymmetry.

1.4.3 Facial electromyography

Facial electromyography (fEMG) is the measure of myoelectrical potentials on the surface of the skin (Ravaja, 2004). Electrical activity, and more precisely voltage fluctuations within the striated muscles (Cacioppo et al., 2007) is investigated by placing two electrodes on skin. A current running through the electrodes composes the signal. fEMG is employed to determine the emotional pleasantness of a given situation. Pleasantness, known as emotional valence, can be successfully determined by fEMG because it is able to detect even minor changes in facial expressions, which possibly would not be detected by eye observation (Ravaja, 2004).

In studies of emotional valence, electrodes are placed on three standard locations: zygomaticus major (ZYG), corrugator supercilii (CRG), and orbicularis oculi (ORB). ZYG muscle area—the cheek area that activates when smiling—is seen to show increased activation while experiencing pleasant emotions. While experiencing negative emotions, increased activity can be obseved on CRG muscle area, which is the brow area that wrinkles while frowning (Ravaja et al., 2006). ORB muscle area, which is located close to the eyelids, activates while experiencing enjoyment smile during highly arousing positive emotional states (Ravaja, 2004). The more activation in a certain muscle, the more affective the situation appears to be for an individual.

1.5 Psychophysiological synchrony

Psychophysiological synchrony is measured to reveal relationships between different indices of one or more signals. Synchrony can be defined either inter-individually or intra-individually. There is no single approach for determining the synchrony, but one often employed approach is to investigate pairwise correlations (e.g. Kuhlen et al., 2012; Kawasaki et al., 2018; Müller and Lindenberger, 2014). Other possible approaches are time-frequency coherence (e.g. Orini et al., 2011), linear time series approaches (e.g. Brillinger, 2001) and non-linear phase synchronization (e.g. Quiroga et al., 2002).

By measuring synchrony it is possible to investigate the underlying processes affecting and present in everyday behavior, such as performance under exciting circumstances, or social interaction in different settings, with greater detail. Inter-individual synchrony has gained increasing amount of attention in studies of empathy research (Soto and Levenson, 2009), interactive decision making (Hu et al., 2018), group work (Henning et al., 2009), interactive gaming (Järvelä et al., 2014), and mimicking (Chartrand and Bargh, 1999), to give a few examples. Inter-individual brain signals have seen to synchronize during social interaction (e.g. Dumas et al., 2010; Yun et al., 2012; Kinreich et al., 2017). In addition, involvement of strong emotions seems to increase brains' synchronization (Nummenmaa et al., 2012).

However, intra-individual synchronization has received considerably less attention, as there are only a few studies investigating physiological synchrony from the perspective of emotion research. One reason for the lack of attention is the difficulty of defining and creating an index that would precisely reflect emotional synchrony. Yet, as emotions are investigated from theoretical, behavioral, physiological and philosophical perspectives, it would be important to find evidence whether and how these different aspects converge within a body. Hsieh et al. (2011) noted that almost all research of emotional synchrony relies upon pairwise analyses and there is lack of evidence on system-wise synchronization utilizing more perspectives and more complex analyses. Hsieh et al. (2011) created an approach to overcome some of the earlier methodology limitations by constructing a dynamic system, including experimental, behavioral and physiological emotion measures. They extended the approach of pairwise analyses—first they calculated Spearman rank-correlations between the variables, added them into a multivariate matrix and used hierarchical clustering for measuring stronger and weaker relationships by examining the distances between variables. Lastly, they taught a network model based on the probabilities of connection and distance metrics computed in the previous steps (Hsieh et al., 2011).

Another example of measuring multivariate synchrony concerns a latent variable approach for time-frequency relationship. Kelava et al. (2015) created a method that combines information from three different signals: ECG, EDA and respiration. The first step was to conduct pairwise comparisons between physiological signals by combining time-series information with frequency distribution, resulting as a new distribution reflecting non-stationary coherence of the signals varying over time. Non-stationarity means that mean and covariance of the signal varies in time, thus all physiological signals are non-stationary. In the second step they conducted a system-wise coherence measure by creating a state-space algorithm that employs the previously created pairwise coherence metrics, and used this information to create a new latent variable of the overall system-wise synchrony. Kelava et al. (2015) way of conducting pairwise comparisons differs from the pairwise comparisons approaches that relay on assumptions of stationarity, e.g. correlation coefficients. This approach introduces a way of investigating synchronization of multiple time-varying signals by taking properties of signals into account, as non-stationary signals are analyzed with non-stationary methods. Therefore, by using a method that takes the properties of the signals into account, less compromises are needed. For example, by measuring pairwise correlations between given time points or events, some degree of information about the signal is excluded. Time-frequency approach allows to investigate properties of the signals more extensively, and may reveal something missed by simpler methods.

In this thesis, a new definition for emotional physiological synchrony is presented, based on the similarity between physiological responses over time. It is also investigated whether synchrony is related to cognitive performance. The research question this thesis investigates is: Does synchrony of emotional responses predict cognitive performance?

2 Methods

2.1 Subjects

The experiment included 32 subjects, 19 females and 13 males. Background information was gathered in the beginning of the experiment including age (19-34 years, mean 26.4, SD 3.8), the highest education (11 high school degree, 14 university first degree, 7 university second degree), handedness (29 right, 3 right/both), language knowledge, and ethnicity.

2.2 Design

Experimental design consisted of 5 different tasks: Mental Imagery, Mental Arithmetic, Visual Search, Emotional Images and Audio. The five tasks were presented to each subject in randomized order. Depending on the subjects' language preferences, it was possible to complete the experiment in either English or in Finnish. Every task was trial-based, and every trial was separated from the next by an inter-stimulus interval of 40 s of visual static (white noise) played onscreen. Inter-task baselines were also recorded with 180 s of white noise. Long inter-stimulus intervals were used to allow physiological signals to recover from effects of prior stimuli.

In the Mental Imagery task, subjects recalled their own emotional memories, one memory at a time, for ten seconds. Nine different emotions were included: fear, anger, joy, enthusiasm, depression, relaxation, triumph, empathy and disgust. Each memory was repeated 6 times in a random order. Subjects saw the name of the emotion on the screen until they felt ready to press a button indicating they would start remembering the evocative incident. After the last trial, subjects were asked to self-evaluate the amount of repulsion and attraction they felt during the task. Answers were given on a 7-point Likert scale varying from "1=Not much" to

"7=Very much".

In the Mental Arithmetic task, subjects were instructed to answer a series of subtraction problems. The task was to continuously subtract the subtrahend from the minuend. There were 3 difficulty levels, every level consisting of 5 trials, resulting in 15 trials. Every trial had a length of 30 seconds. Each difficulty level started with the easiest trial and ended in the most difficult one. Subjects received audiovisual feedback on whether or not they answered correctly. If a wrong answer was given, the correct answer was shown on a screen to inform where to continue calculating from. After each answer, the total percentage of correct answers was shown on the screen. After the last trial, subjects were asked to rate how focused (1=unfocused, 7=focused/sharp) and stressed (1=relaxed/unstressed, 7=tense/stressed) they felt during the experiment.

The Visual Search task consisted of 3 different categories: Where's Waldo, Multipath Mazes, and Odd-one-out. In Where's Waldo subjects were instructed to find the character Waldo depicted in a visually noisy scene. In Multipath Mazes, subjects saw pictures of a labyrinth, in which an entrance was marked and the task was to find the correct exit. In Odd-one-out pictures included numbers and one letter, or vice versa, and the task was to spot the singleton alphanumeric. Each category included 3 difficulty levels, and every trial was 30 s, resulting in 9 trials. After the last trial, subjects were asked to rate how focused (1=unfocused, 7=focused/sharp) and stressed (1=relaxed/unstressed, 7=tense/stressed) they felt during the experiment.

In the Emotional Images, the task was to view emotional pictures without needing to respond, only paying attention to the stimuli. Pictures were derived from International Affective Picture System (IAPS) so their normative emotional valence and arousal were known. Each picture was presented for 8 seconds followed by inter-stimulus interval.

In the Audio, subjects were instructed to listen to audio clips without needing to respond to them. Audio clips were derived from International Affective Digitised Sound (IADS) database, so their emotional valence and arousal were initially known. In addition to the audio clips, subjects were also presented auditory stimulus which demanded a response: they were instructed to focus on a specific number while hearing different numbers. At the end of the trial they were asked what the initial number was. Each audio stimulus was presented for 8 seconds followed by inter-stimulus interval. After the last trial, subjects were asked how focused (1=unfocused/bored, 7=focused/sharp) they felt during the task.

2.3 Procedure

After entering the lab, subjects were provided with an informed consent form regarding the experiment and informed that 3 subjects with the best performances, would receive a money award worth of 40 euros.

After the briefing, electrodes were attached to subjects. For the recordings, the VarioPort ARM portable amplifier/ADC (analog-digital converter) was worn by subjects. VarioPort was connected to a laptop via Bluetooth in order to send streaming data.

The system ground electrode was attached on the back of the neck.

ECG electrodes were attached at the manubrium (jugular notch) and lower left rib, using electrodes with stud connector 35 x 45 mm (Spes Medica S.r.l.). ECG was sampled at 64Hz.

fEMG was recorded at three separate sites: the muscle regions Corrugator Supercilii (above the brow, indexes negative emotion), Zygomaticus Major (on the cheek, indexes positive emotion) and Orbicularis Oculi (below the eye, indexes sincere positive emotion). Electrodes were filled with Synapse conductive electrode cream (Med-Tek/Synapse, Arcadia, CA), impedances were ensured to be below 10kΩ, and signal was sampled at 1024Hz.

EDA electrodes were attached on the proximal phalanges (the lowest bones of the finger) of non-dominant hand. Electrodes were Ag/AgCl filled with TD-246 skin conductance electrode paste (Med Assoc. Inc.). Signal was sampled at 32Hz.

Six EEG electrodes were mounted in a soft cloth cap and attached at 10/20 electrode sites F3, F4, C3, C4, P3, P4; sites were estimated by aligning the cap vertex halfway between the nasion and inion. Ground electrode was placed at the AFz (on the upper forehead) and the reference electrodes were attached to the ear clips. EEG was sampled at 128Hz. Electrooculography was also recorded under the same settings, with electrodes mounted 2cm above and below the left eye, and 1cm outside the outer canthus of each eye.

Before starting the experiment, electrode impedance was checked and 8 min baseline was recorded. During the experiment, data quality was visually monitored, and the research assistant took notes on any possible confounding factors during the recording.

2.4 Signal processing

Signal processing was performed by taking into account signals' properties and the research purpose. All of the signals included several possible components to extract and further analyse. The most suitable features related with emotion were chosen, being rather the phasic components of the signal than tonic (except for EEG, from which oscillatory power was chosen). For each signal, five time slices were extracted from the emotion elicitation period. Because each physiological signal measures a process which elapses on slightly different time scales (e.g. EDA responds to a stimulus more slowly than fEMG), the time slices were defined separately for each signal. The relationship between signals, i.e. their physiological synchrony, is then calculated for corresponding time slices (1 to 5), rather than equivalent moments in time.

In this study, ECG was not processed further because it did not suit the duration of analyses, and EOG was not included due to the lack of suitable hypothesis concerning emotion research.

2.4.1 EDA

EDA was preprocessed with the Ledalab toolbox v3.4.9 for Matlab r2019 (Benedek and Kaernbach, 2010). Downsampling of the signal was conducted to 16 hZ and filtering was carried out with Butterford low-pass filter with a cut-off criterion of 4 Hz. Data quality was first visually inspected, and then artefacts were interpolated. Data smoothing was performed with a Gaussian window of 20 samples' width. Continuous decomposition analysis, based on the non-negative deconvolution method (Benedek and Kaernbach, 2010), was carried out for separating the phasic and tonic components of the signal. Three optimization cycles were performed. Lastly, each event-related feature was exported from Ledalab as 5 time-segments, each segment having duration of 2 seconds, sequentially after each event.

2.4.2 EEG

EEG processing was conducted using the CTAP (Cowley et al., 2017; Cowley and Korpela, 2018) and EEGLAB toolboxes for Matlab r2019. Data was re-referenced to average reference, and band-pass filtered to 1-45 Hz. First round of bad channel detection was conducted by FASTER tool (Nolan et al., 2010). None of the channels was detected as bad by using these settings. Next, data was manually segmented starting from the beginning of the Mental Imagery and ending after the task. Blink detection and labeling was performed with CTAP's inbuilt function that is based on the method by Toivanen et al. (2015). Data quality was then visually inspected, and 4 subjects whose data quality was not good, were discarded from further analysis. Next, for data segments around the emotion events (from 5 seconds before the emotion until 15 seconds after the emotion) detected blinks were manually reviewed and removed along with other signal distorting activity such as chewing and yawning. Signal removal was achieved by cutting the data around the artefact (no blind source separation methods could be used due to having only 6 channels). After cleaning the data, if the length of the resulting signal, starting from the emotion response and ending at the following white noise period, was less than 4 seconds, epoch was excluded from further analysis.

Spectral features of the EEG were computed by Welch periodogram, including band powers in the canonical frequency bands delta, theta, alpha, beta, gamma. These were exported as 5 time-segments, each of duration 1 second, with segments distributed throughout the 10 second emotion-elicitation event so as to minimise overlap with (a) any boundary events caused by artefact rejection (by custom code), or (b) with each other if less than 5 seconds clean data remained. Due to noisy parts in the EEG signal, some of the trials had to be discarded. For 11 subjects, this resulted in less data, but never under 85 percent out of the maximum.

2.4.3 fEMG

fEMG processing was conducted in the Anslab toolbox for Matlab. The data quality was first visually inspected and then rectification of the data was performed. Each event-related amplitude was exported from Anslab as 5 time-segments, each segment having duration of 1 second, sequentially after each event.

2.5 Statistical methods

After processing the physiological data, different signals were combined by creating a method of emotional synchrony. The method consists of two approaches, Approach 1 investigating patterns of physiological responses within one emotion, and Approach 2 investigating patterns of physiological responses between two emotions. Both approaches employ Kendall correlation and cosine similarity analysis. The similarity of emotional responses—emotional synchronization—is investigated at the level of an individual, and the relationship between synchronization and cognitive performance is investigated at the group level by deriving linear regression models.

2.5.1 The new method

To investigate how different emotions may elicit similar activation, cosine similarity was used to determine the distance between emotions. Cosine similarity is a measure of the cosine of the angle between two non-zero vectors in an inner product space, and it provides the similarity of the orientation between the two vectors. If the angle between the vectors is 90°, their cosine similarity is 0. If this angle is 0°, their cosine similarity is 1. Cosine similarity can also be calculated in a negative space. Within this thesis, cosine similarity was conceptualized as reflecting the amount of synchrony.

As previously described, subjects aroused their emotional memories while their physiology was recorded. There was an equal amount of physiological information about each emotion, as all of the signals were recorded simultaneously. This physiological information was analyzed as separate features representing different indices of the emotional process, although the features are not independent since some of them may reflect similar cognitive processes.

Table 1: Physiological features and the processes they reflect

Feature	Abbreviation	Physiological process
Skin conductance response	SCR	Arousal
Frontal alpha asymmetry	FASYM	Attention, motivation
Corrugator supercilii	CRG	Negative valence
Zygomaticus major	ZYG	Positive valence
Orbicularis oculi	ORB	Highly arousing positive valence

To create a measure of emotional synchrony, signals were binned into five time slices taken from the 10 second time windows during which participants recalled their emotional memories — separately for each signal as described above.

The method of emotional synchronization consisted of two different approaches that both employ Kendall correlation and cosine similarity analysis. Approach 1 is used for investigating synchrony patterns of physiological responses within one emotion, and Approach 2 for investigating synchrony patterns of physiological responses between two emotions. Both approaches are used separately.

Approach 1 was created as follows. First, within a trial, Kendall correlation was calculated between time order and each 2 second time slice representing physiological activity. Altogether, this results in a vector of 6 values for each subject, which corresponds with the amount of trials per emotion. For subjects whose EEG trials were discarded due to data quality issues, the length of the vector equals the amount of remaining trials. Therefore, each value of the correlation vector represents how physiological activity fluctuates over time. Fluctuation profile of the signal was created for every physiological feature (SCR, FASYM, CRG, ZYG, ORB) in every emotion (anger, depression, disgust, empathy, enthusiasm, fear, joy, relaxation, triumph). For instance, one fluctuation profile would represent SCR during anger, while another would represent CRG during anger.

Second, cosine similarity was calculated between two correlation vectors resulting in a cosine similarity value representing synchrony between two features within one emotion. In other words, if two correlation vectors have similar fluctuation profiles over time, it results in a high cosine similarity value indicating high synchronization of the patterns of physiological responses over time. If two correlation vectors tend to have opposite fluctuation profiles over time, it results in highly negative cosine similarity value. If there seems to be no relationship between the two fluctuation profiles over time—for example, if patterns of responses between SCR and CRG during anger are not related—it results as a cosine similarity value close to zero indicating fluctuation profiles of SCR and CRG are independent rather than synchronous. Cosine similarities were calculated for all possible combinations of physiological features, in each emotion. For example, cosine similarity was calculated between the fluctuation profile of SCR during anger and the fluctuation profile of CRG during anger; likewise for disgust, etc. Therefore, obtained cosine similarity values reflect the amount of synchronization between two different physiological responses within one emotion.

Approach 2 was created to further investigate patterns in the data. First, for each of the 5 time slices, the average of all 6 trials was calculated for every physiological feature in each emotion. These averages compress the information over all trials. For example, first average could be an average of the first two second SCR activity during anger over the 6 trials, second average could be an average of the next two second SCR activity during anger over the 6 trials and so on.

Second, Kendall correlation was calculated between the averaged physiology values and time order. This procedure was repeated for every physiological feature in each emotion, resulting in one correlation for every physiological feature in each emotion. Individual correlations compose a feature vector, the length of which equals the amount of chosen physiological features. An example could be a vector representing the averaged fluctuation profiles of SCR, FASYM, CRG, ZYG and ORB responses over time during anger, and another vector representing fluctuation profiles of SCR, FASYM, CRG, ZYG and ORB responses over time during depression.

Lastly, cosine similarity was calculated between two correlation vectors resulting in a cosine similarity value representing the synchrony of chosen physiological features in two different emotions. As in Approach 1, obtained cosine similarity value reflects synchrony between two vectors. The key difference between the approaches is, that in Approach 1 the synchrony represents similarity of two different physiological fluctuation profiles within one emotion, while in Approach 2 synchrony represents the similarity of multiple averaged fluctuation profiles between two different emotions. To continue with the previous example, in Approach 2, high synchrony between the correlation vector (composing of the averaged fluctuation profiles of SCR, FASYM, CRG, ZYG and ORB) in anger and correlation vector (composing of the averaged fluctuation profiles of SCR, FASYM, CRG, ZYG and ORB) in depression would indicate strongly similar physiological responses between two different emotions.

2.5.2 Performance

Responses from the three Visual Search task types were pooled, and the percentage of correct answers was used as an index of performance. In addition, median and variance of the reaction time were derived. For Mental Arithmetic task, responses of different difficulty levels were pooled. Performance was scored based on the proportion to the highest amount of arithmetical problems solved, i.e. the subject who achieved the highest amount received a score of 100% and other subjects were scored proportionately. Median of the reaction time and reaction time variance were also calculated for arithmetic condition. Thus, a total of 6 performance metrics per each subject were obtained.

3 Analysis and results

Out of 32 subjects, emotional synchrony was successfully calculated for 27 subjects in both approaches. The physiological and performance data of 5 subjects was discarded. Analysis started with Approach 1 for determining the emotional synchrony within one emotion, and then by investigating how the synchrony is related with performance. Analysis was then continued with Approach 2 for determining the emotional synchrony between two emotions, followed by investigating its relation to performance.

3.1 Approach 1

By using Approach 1, synchrony values were calculated between all possible feature pair combinations, separately for each emotion and individually for each subject. This resulted in 90 synchrony values per subject (9 emotions x 10 feature pairs).

Next, mean values over all above mentioned synchrony values were calculated by combining all emotions and all subjects (Table 2). Majority or the mean values tend to locate close to zero, varying from -0.04 to 0.40 (median=0.01, SD=0.13) except the mean of ZYG-ORB feature pair, having the highest value of 0.40.

Table 2: Synchrony values between feature combinations over all emotions and subjects

Feature pair	Sync	Feature pair	Sync
SCR-CRG	-0.04	ORB-CRG	0.11
SCR-FASYM	0.03	ORB-FASYM	0.02
SCR-ORB	-0.02	ZYG-CRG	0.01
SCR-ZYG	-0.02	ZYG-FASYM	0.01
CRG-FASYM	-0.04	ZYG-ORB	0.40

Next step was to investigate every emotion individually. Means for all pairwise combinations were calculated separately for each emotion, combining all subjects (Table 3). Mean values varied from 0 – 0.13 (median=0.05, SD=0.04).

Table 3: Descriptive stats of synchrony values for each emotion

Emotion	Mean	Median	SD
Anger	0.13	0.06	0.14
Disgust	0.07	0.04	0.16
Fear	0.05	0.04	0.11
Depression	0.06	0.05	0.12
Empathy	0	-0.02	0.11
Relaxation	0.02	0.01	0.14
Enthusiasm	0.07	0.04	0.18
Joy	0.03	-0.05	0.22
Triumph	0.02	-0.05	0.23

To investigate patterns of feature pair behavior in more detail, means for every feature pair were calculated separately for each emotion. Therefore, 9 different tables including 10 feature pairs were created. To save space, these tables are not presented here. The synchrony of ZYG-ORB feature pair was clearly strongest in emotions of high arousal and positive valence, as can be seen in Table 4. This was the only feature pair repeatedly showing strongly similar physiological response patterns with values varying from 0.22 to 0.63 (median=0.35, SD=0.15). Rest of the feature pairs showed less similar response patterns values varying from –0.19 to 0.32 (median=0.01, SD=0.10).

Table 4: Emotion specific synchrony values for the ZYG-ORB feature pair

Emotion	Sync
Anger	0.35
Disgust	0.37
Fear	0.22
Depression	0.34
Empathy	0.24
Relaxation	0.35
Enthusiasm	0.54
Joy	0.63
Triumph	0.61

To further continue the analysis of emotion-specific feature pair behavior, synchrony value of 0.2 was chosen as the threshold. In addition, only those above-threshold feature pairs whose activation was associated with the valence of emotion (see Table 1) were considered as important to analyze further. Synchrony values of the feature pairs that exceeded threshold are presented in Table 5. As can be seen, this was true for 6 emotions: anger, empathy, relaxation, enthusiasm, joy and triumph. Feature pairs that exceeded threshold were ZYG-ORB in every other emotion except for anger, where criterion was exceed by the pair of SCR-FASYM.

Table 5: Feature pairs that exceed the threshold criterion of 0.2

Emotion	Feature pair	Sync
Anger	SCR, FASYM	0.21
Empathy	ZYG, ORB	0.24
Relaxation	ZYG, ORB	0.35
Enthusiasm	ZYG, ORB	0.54
Joy	ZYG, ORB	0.63
Triumph	ZYG, ORB	0.61

Next, linear models were derived to investigate the relationship between the above-threshold cosine similarity values and performance. Models were created individually for each feature pair using performance score as a dependent variable and cosine similarity value as an independent variable. This resulted in 36 models, due to the 6 emotions including above-threshold feature pairs and 6 different performance metrics. Most of the models did not reveal interesting neither significant relationships. One interesting pattern occurred, as the relationship between correct answers in Visual Search and highly arousing positive emotions was positive and increasing, indicating that the higher the synchrony of ZYG-ORB feature pair, the more correct answers were given in Visual Search tasks. Created models and their Holm-corrected p-values are presented in Table 6, showing a stable effect on the ZYG-ORB feature pair across highly arousing positive emotions.

Table 6: Linear models on highly arousing positive emotions and performance

DV	IV	B	SE	r^2	t	p	adj p
visAcc	Enthusiasm	0.03	0.02	0.11	1.87	0.07	0.14
visAcc	Joy	0.05	0.03	0.10	1.77	0.09	0.14
visAcc	Triumph	0.04	0.02	0.19	2.61	0.01	0.04

*For all emotions, used feature pair is ZYG and ORB

3.2 Approach 2

Analysis was continued with Approach 2, following the results of Approach 1 that revealed synchrony indices being highest in emotions of high arousal and positive valence. To further investigate how similar the response patterns were between these emotions, analysis was continued by calculating synchrony indices between the following pairs: enthusiasm and joy, enthusiasm and triumph, triumph and joy. Same features were used as in the Approach 1 (SCR, ZYG, ORB, CRG and FASYM). Emotion pairs tend to have quite similar response patterns, as descriptive statistics in Table 7 show, calculated over all subjects' synchrony values.

Table 7: Descriptive stats for highly arousing, positively valenced emotion pairs

Emotion pair	Mean	Median	SD
Enthusiasm, Joy	0.50	0.50	0.30
Enthusiasm, Triumph	0.45	0.58	0.41
Triumph, Joy	0.41	0.51	0.42

As Approach 1 revealed, Visual Search was the only task type that was related with emotional synchrony. Therefore, relationship between Visual Search performance and synchrony was further explored by plotting the performance scores against synchrony indices of each emotion pair, as Figure 2 shows.

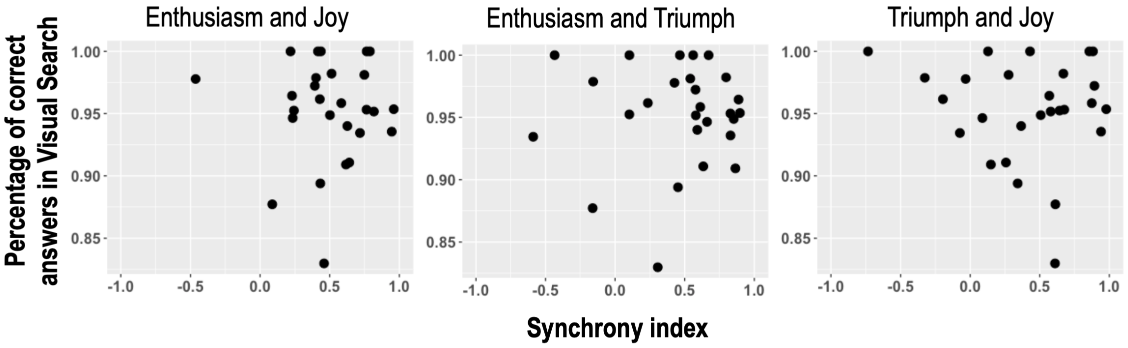

Figure 2: Visual Search performance scores plotted against Synchrony indices

To investigate whether the tendency to respond similarly to different highly arousing positive emotions is linked with performance in Visual Search tasks, linear models were derived. Performance on Visual Search tasks was the dependent variable and synchrony value was the independent variable. Separate models were created for every emotion pair. Linear models revealed that the similarity of responses in highly arousing positive emotions was not related with performance in Visual Search tasks.

4 Discussion

The interest in investigating physiological synchrony comes from the intention to achieve a more comprehensive understanding of the bodily functions underlying emotion. Since one signal can only partly explain connections between physiology and psychology (Ravaja, 2004), multiple signals are required to increase the specificity and sensitivity of the investigated relationships (Cacioppo and Tassinary, 1990). Yet, these metrics are generally thought challenging to determine. One reason for the difficulty is suggested to be the lack of suitable methodology (e.g. Hsieh et al., 2011; Kelava et al., 2015). Despite different proposed approaches, there is no established practice for determining emotional synchrony. Here, a new method for determining emotional synchrony is presented. This method is based on cosine similarity analysis for measuring the similarity between different emotional responses over time. Cosine similarity has not been previously used to investigate physiological activity patterns of emotions.

To investigate whether emotional synchrony is related with behavior, cognitive performance was measured. The main research question of this thesis sought to integrate synchrony of emotional responses with cognitive performance. It is investigated whether emotional synchrony predicts performance under two cognitively loading task types, Mental Arithmetic and Visual Search. It is found that two facial muscles—ORB and ZYG, whose activation is associated with pleasant emotions—have strongly similar activity patterns during highly arousing and positively valenced emotions: enthusiasm, joy and triumph. This supports prior research (e.g. Lang et al., 1993; Cacioppo et al., 2000) on these muscles activation being an indicator of experienced pleasantness. Furthermore, it was shown the synchronization of ORB and ZYG had a stable effect of indicating better cognitive performance in Visual Search task.

4.1 Emotional synchrony

Cosine similarity analysis is a novel approach for investigating the similarity of responses in emotion research. Therefore, this study was exploratory, but influenced by existing approaches to determining physiological synchronization.

Kelava et al. (2015) represented pairwise signals coupling over time by first defining the pairwise relationships based on a data transformation of overlapping time sequences. The resulting pairwise coherence that varies over-time was represented as a time-frequency plot containing the signals' spectral features in a certain time moment. The overall synchrony was then determined based on the obtained pairwise coherence metrics by using a state-space modelling approach which is based on defining a latent variable to represent time-frequency synchrony within chosen frequency regions. Hsieh et al. (2011) method for defining synchrony started by calculating pairwise Spearman rank correlations between the different levels of emotion measures (e.g. behavioral and physiological) from which they then created a multivariate matrix. Relationships of the variables were located in a multivariate matrix and investigated by hierarchical clustering, thus extending the analysis beyond pairwise comparisons—which revealed the strength of the connections between the variables. Based on the connection metrics, they calculated probability distribution showing the amount of coherence and revealing the distance between the different emotion variables.

These examples of defining synchrony indices for emotion data demonstrate different approaches to model connection between signals. In this study, the approach to model the signals' profile over time was based on correlating signals' frequency distribution with time moments by using Kendall rank correlation. Resulting correlations represents how physiological signal evolves with time. By calculating synchrony between the signals correlated with time, it is possible to know: 1) how similar the fluctuation profile of two different signals is during the same emotion 2) how similar the fluctuation profile of multiple signals is between two different emotions.

4.2 Cognitive performance

Synchrony of responses in the fluctuation profiles in ORB and ZYG during highly arousing positive emotions indicated better performance in Visual Search tasks. However, any causal claim of higher synchrony causing better performance in Visual Search could not be made as different task types in the experiment were presented in a random order, meaning some subjects accomplished Visual Search before eliciting their emotions on Mental Imagery. Instead, the tendency to have highly similar physiological response patterns in ORB and ZYG—in other words, signals' tendency to synchronize—indicated there was also a tendency to score higher in Visual Search.

No relationship between synchrony indices and Mental Arithmetic was detected.

The difference in performance might be explained by the slightly different cognitive processes needed in Visual Search and Mental Arithmetic. Another explanation could be related to the performance score assessment. In Visual Search this was based on the correct amount of answers, while in Mental Arithmetic the score was based on the amount of answered problems. Therefore, subjects who answered the most, did not necessarily receive the highest percent of correct answers, as the game was not finished by the wrong answers. As Hitch (1978) note, strategies for solving arithmetical problems vary between individuals, making it possible that some subjects had more successful strategies. If this was the case, it would not be surprising that a similar synchrony-performance effect was not present in Mental Arithmetic as was in Visual Search. For instance, if a subject was anxious and hurried from one question to another, it would be possible to give many answers, including wrong ones, while still receiving a high score in Mental Arithmetic.

4.3 Limitations and Future work

One challenge of psychophysiology concerns its ambiguity, as there is never full certainty that the measured physiological activation is emotion-related and not caused by other homeostatic functions, such as hormones or thermal regulation. Research has not revealed a special fingerprint for any emotion (e.g. Barrett, 2017), thus making it impossible to know whether the measured physiological activity of emotion actually reflects the emotion under study. In the experimental study presented in this thesis, it could only be assumed the subjects tried their best to elicit the emotion. In future research, it could be beneficial to combine physiological measurements and self-reports. Although self-reports are criticized as an inaccurate method for investigating emotions, by asking subjects how well they succeeded to elicit the given emotions, it could be possible to gain a more accurate understanding whether their experience during the experiment were equivalent with their real-life emotional experiences.

Another limitation concerns the novelty of the investigated phenomena (Approach 1 and 2). Since the presented cosine similarity analysis has not been previously used in emotion research, previous discussions of interpretational issues do not exist. Therefore the threshold at which high cosine similarity value indicates strong synchronization is still unclear. The method presented here needs further investigation, so that its relation to other existing synchrony measures could be addressed.

5 Conclusion

This study examined physiological connections during emotion, and investigated whether emotional synchrony predicts cognitive performance. In an experimental study, emotional intra-individual synchrony was determined based on the subjects' physiological activity during the Mental Imagery task, in which they recalled their emotional memories. Cognitive performance was measured by using Visual Search and Mental Arithmetic tasks. Three physiological signals—EDA, EEG, fEMG—were recorded during the study. The aim of the thesis was to investigate whether the synchrony of emotional responses predicts cognitive performance. Altogether, this study contributes to research in emotional synchrony. First, a new method for determining emotional physiological synchrony was created. Second, it was found that strong synchronization between facial muscles ZYG and ORB corresponded to the positiveness of emotions having strongest activation during highly arousing positive emotions. This synchrony was related with improved performance in Visual Search tasks.

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