Master thesis on Cognitive Systems and Interactive Media

Universitat Pompeu Fabra

Studying the physiological relationship between Cognitive Flexibility and Moral Decision-Making

Sajad Kahali

Supervisor: Ismael T. Freire

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SPECS

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Table of Contents

Abstract

As a human, moral decision-making plays a crucial role in our life because the consequences of our decisions affect others' welfare. Our physiological changes (i.e., increased heart rate) might influence our judgment. Furthermore, our ability to deal with the outcomes of our decisions is essential to move on with our lives. This study investigates the physiological relationship between cognitive flexibility, which commonly refers to the ability to shift cognitive set to perceive and respond to situational demands and moral decision-making. Heart rate variability (HRV), the time intervals between adjacent heartbeats change, and pupil dilation are being used as biomarkers to observe our physiological changes when facing new circumstances. The Wisconsin Card Sorting Test (WCST) measures cognitive flexibility and a set of moral dilemmas in the virtual environment employed for moral decision-making tasks. Our findings demonstrate a positive correlation (not statistically significant) between cognitive flexibility and variability in the deontological and utilitarian decisions. A positive correlation (not statistically significant) has been found between resting state HRV and cognitive flexibility. A negative correlation (not statistically significant) is seen between resting state HRV and consistency in moral decision-making. We compared our participants' reports with their pupil behavior when facing different moral contexts. A positive correlation (not statistically significant) has been noticed between the reports and pupils' diameter changes when they face a moral decision-making task. Although none of our findings were statistically significant, this research contains great prospects for enhancing our understanding of the link between cognitive flexibility and moral decision-making.

Keywords: Cognitive flexibility; Moral decision-making; Heart rate variability; Pupil dilation

1. Introduction

As a human, one of the most repetitive tasks we face in our daily lives is making a decision, and the influence of the outcome of our decision will lead us to the next choice. One side of this decision-making spectrum can start from our practical choices in our daily tasks, such as deciding what to wear and what to eat for lunch. Conversely, it can be a philosophical decision, i.e., choosing a lifestyle. Choosing between different options can get more complicated when we are not the only ones that receive the consequences, but also the result of our decision will impact others. When we want to execute our decision, we may feel stressed from one standpoint and experience an increase in our heart rate, influencing our judgment. From the other standpoint, we may feel responsible and reevaluate the situation from a moral perspective before making our decision. We will experience a new situation based on the result of our decision. To move forward in our life progress, regardless of the consequences of our choices, being flexible and adaptive to the new situation is needed. Hence, moral decision-making and adaptation will play an essential role in our life.

A few attempts have been made to study the relationship between cognitive flexibility and moral decision-making. This thesis builds on these findings and focuses on the physiological relationship between cognitive flexibility and moral decision-making.

1.1. Cognitive Flexibility

1.1.1. Executive functions

Adaptation of the cognitive process is a crucial element in our evolution and a vital factor for our survival as a species. It is easier and effortless to remain in the current state than to think and evaluate to change the situation. We need to resist the temptation of "not changing" to respond to a new change in our environment. An essential concept in the changing process is "Executive functions (EFs)." Inhibition (inhibitory control, including self-control and interference control), working memory, and cognitive flexibility are the three core of EFs. Reasoning, problem-solving, and planning are built based on these cores of EFs[1].

"Cognitive flexibility commonly refers to the ability to shift cognitive set, aptitude, thought, or attention in order to perceive, process, or respond to situations in different ways."[2,3] Cognitive flexibility is composed of two parameters: reactive flexibility and spontaneous flexibility.

(1) Reactive flexibility: represents the ability to shift cognition or behavior in response to new changes in the environment voluntarily and of one's own volition.
(2) Spontaneous flexibility: refers to divergent thinking, contemplating alternatives, and adjusting plans[2,3].

In the neuroscience literature, the term "Cognitive flexibility" and "Behavioral flexibility" are used alike, and the terminology difference is due to the way the concepts has been mentioned in different disciplines (Cognitive psychology and behavioral neuroscience, respectively). Behavioral flexibility refers to the ability of behavioral adaptation to new circumstances[4].

1.1.2. Cognitive flexibility: attention and knowledge

Attentional processes and knowledge representation are needed to be cognitively flexible. Attention is a crucial part of cognitive flexibility to detect new environmental changes. On the other hand, knowledge is a vital aspect of learning from similar experiences which had happened before, and the values of the environmental factors have been shaped through those experiences. A person needs to deduce that a new approach is required to respond to the stimuli; the person's knowledge needs to be adjusted. Thus, these people can redesign their knowledge quickly; hence their responses to new changes in the environment are functional[5]. To achieve this, the organism must be able to flexibly adapt and switch between different cognitive and decision-making systems[6,7].

1.1.3. Cognitive inflexibility: failing to adjust to changes in the environment

Four concepts associated with cognitive inflexibility have been studied in the realm of Psychology of Thinking: cognitive blockade, cognitive hysteresis, functional fixation, and functional reduction.

(1) **Cognitive blockade**: the person is focused on a particular task and ignores the rest. However, the situation parameters have changed; they continue with the same pattern of actions and decisions.
(2) **Cognitive hysteresis** (cognitive narrowing or tunnel vision): refers to the condition that a person has failed to evaluate the situation correctly and cannot reconsider the circumstances after an action has been made to handle the situation.
(3) **Functional fixation**: the person has a rigid perception of using daily objects. The fixation impedes them from using an object in a new method or context and prevents them from using it in the same context but in different sequences.
(4) **Functional reduction**: refers to a condition in which the person cannot consider all possibilities that cause a problem. They hold to a specific reason and ignore the other practical elements.

These four phenomena in cognitive inflexibility cause a wrong evaluation of the environment and lead the person to discrete responses. Hence, people with impaired cognitive flexibility have difficulties engaging in new situational demands[5].

1.2. Moral judgment

1.2.1. Moral judgment: Utilitarian vs. Deontological

One of the most complex situations any human is experiencing is a moral dilemma. Consider one classic puzzle, the trolley dilemma (Figure 1); a trolley is hurtling out of control on its track and leaning toward five workers who will die if you do nothing. A large man and you are standing on a footbridge above the track. In order to stop the trolley, you can flip a switch that releases a trapdoor, dropping the large man onto the track, where his body can prevent the trolley. Is it morally permitted to kill one man but save the five workers by flipping the switch?[8] Literature reviews demonstrate several definitions of morality that focus on different aspects (e.g., from a normative/prescriptive or empirical/descriptive sense[9]). Amongst different philosophical traditions that try to explain our intuition behind our moral decision-making, these are the two main approaches: Utilitarian and Deontological.

(1) **Utilitarianism**: due to their standpoint, optimizing the amount of "utility" as a measure of happiness is the primary purpose behind morality. Hence, utilitarian evaluation of any action is based on the result of that specific action; they have been called "consequentialists" due to their point of view.

(2) **Deontology**: justifies the actions themselves from a moral perspective despite the action's outcomes. For instance, "killing" is terrible regardless of the cosequences[10].

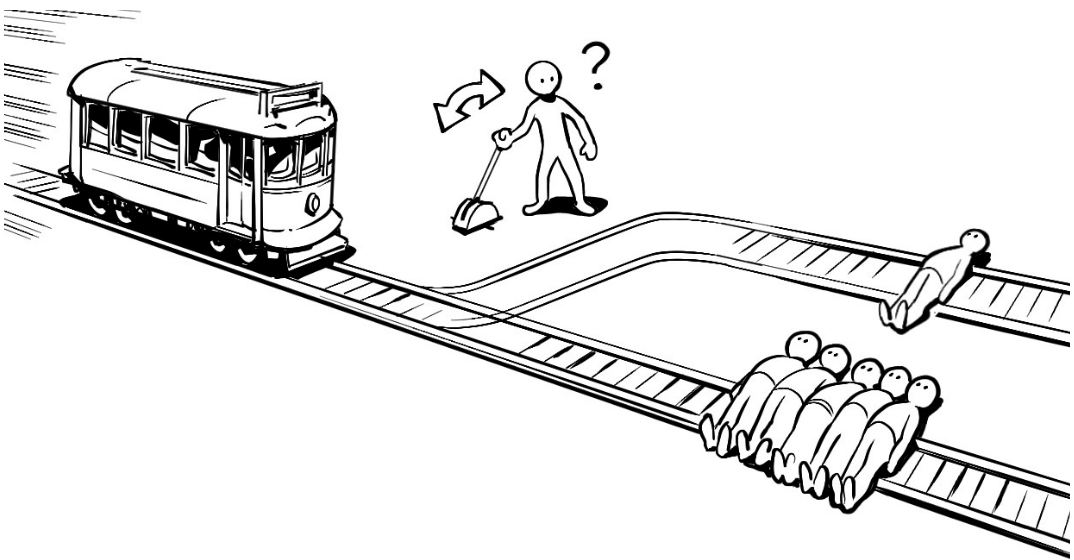

Figure 1: The trolley dilemma. Image adapted from http://www.cienciacognitiva.org

1.2.2. Dual-system theory: intuition vs. rational

The dual-system theory looks at a moral dilemma (e.g., trolley problem) from a different perspective, not solely from an ethical point of view. It explains human judgment, reasoning, and behavior with the characteristic of a dual network (e.g., intuition vs. rational)[11]. It defines the whole process in the realm of two systems, system 1 and system 2 (Figure 2).

(1) **System 1**: moral judgment takes the form of intuition that is accomplished by unconscious, rapid, automatic, and high-capacity processes.

(2) **System 2**: moral judgment is a product of conscious, slow, and deliberative processes[12,13].

Studies have shown that individuals can make decisions based on either consequentialism or deontology because their neural systems work separately[14]. The controlled cognitive process (system 2) is in charge of utilitarian moral judgments, and on the other hand, deontological moral judgments are enabled by intuitive, emotional responses (system 1)[14].

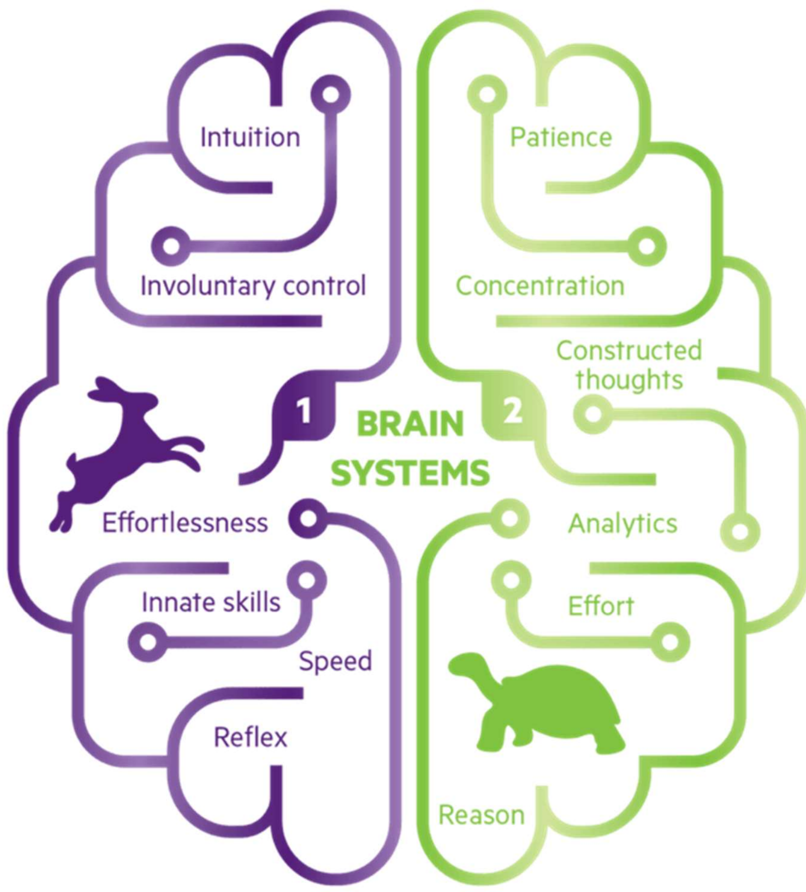

Figure 2: The dual-system theory[12]. Image adapted from https://medium.com

1.2.3. Cognitive systems: computational models

Reinforcement learning literature provides a theoretical formalism describing how cognitive systems might perform from a computational perspective; they offer three computational models: model-based, model-free, and Pavlovian system[8].

(1) **Model-based**: this computational system is the model of system 2, which is mostly in charge of consequentialism; the system makes a decision based on action outcomes (controlled cognitive process).

(2) **Model-free**: this system is the model of system 1, which is in charge of deontology. The system evaluates actions based on their reinforcement history and is mapped to system 1 (intuitive, emotional responses).

(3) **Pavlovian system**: is in charge of automatic reflexive responses to appetitive stimuli and withdrawal reactions to aversive ones. The Pavlovian system can influence the model-based and model-free mechanism: for instance, aversive predictions can suppress the decision-making process in those systems[8].

The so-called moral dilemma, "push-trapdoor divergence," provides a good perspective on the function of the Pavlovian system (Figure 3). In this study, the scenario of the classical trolley problem (where the subject needed to decide between saving one person or five workers' lives by guiding a trolley via pulling a lever) was modified to physical contact (pushing the one person) instead of pulling a lever. This modification changed the result significantly: participants considered physically pushing a person onto the track as less desirable hence they avoided executing the action and were more likely to pull the lever instead. The Pavlovian system plays a critical role in behavioral suppression to prevent an aversive consequence. This approach also can be used for pruning the decision tree in the thinking process or behavioral strategy, which end up in aversive states[15].

In evaluating a situation, all three mechanisms work simultaneously; after the combination of each system "votes" for its preferred response, the final choice has been executed as the outcome[8].

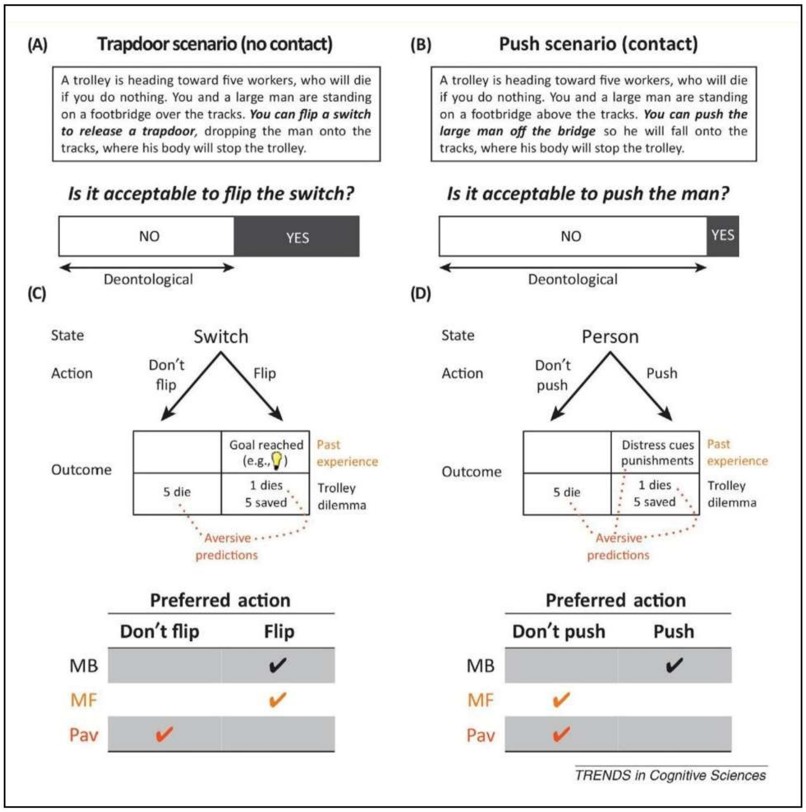

Figure 3: "(A, B) Example trolley scenarios and typical judgment patterns (data adapted from[16]). (C, D) Diagrams mapping links between states, actions, and outcomes, and tables depicting the preferred actions of the model-base (MB), model-free (MF) and Pavlovian (Pav) systems"[8]. Image adapted from [8].

1.3. Physiological perspective

One of the vital aspects of human physiology is the cardiovascular system and its relationship with the nervous system. The essential part of the cardiac cycle is the heart. The human heart is about fist size, and its weight is approximately 250 to 350 g. It beats around 100,000 times per day. The heart consists of two atria and two ventricles. The atria are located above the ventricles. Through the right atrium, deoxygenated blood has entered the heart. It is pumped to the lung from the right ventricle via the pulmonary arteries, where wastes are removed and oxygen is replaced. Oxygenated blood is entered into the heart through the left atrium, and due to the left ventricle contraction, blood is ejected through the aorta to the arterial system[17,18].

1.3.1. Pacemaker: initiating the heartbeat

The heart contains autorhythmic cells; their function is to generate the pacemaker potentials that initiate cardiac contractions. There are two internal pacemakers, the sinoatrial (SA) node and the atrioventricular (AV) node, which initiate the heartbeat. This electrical conduction system and heart muscle contraction are recorded by the electrocardiogram (ECG)[19] (Figure 4).

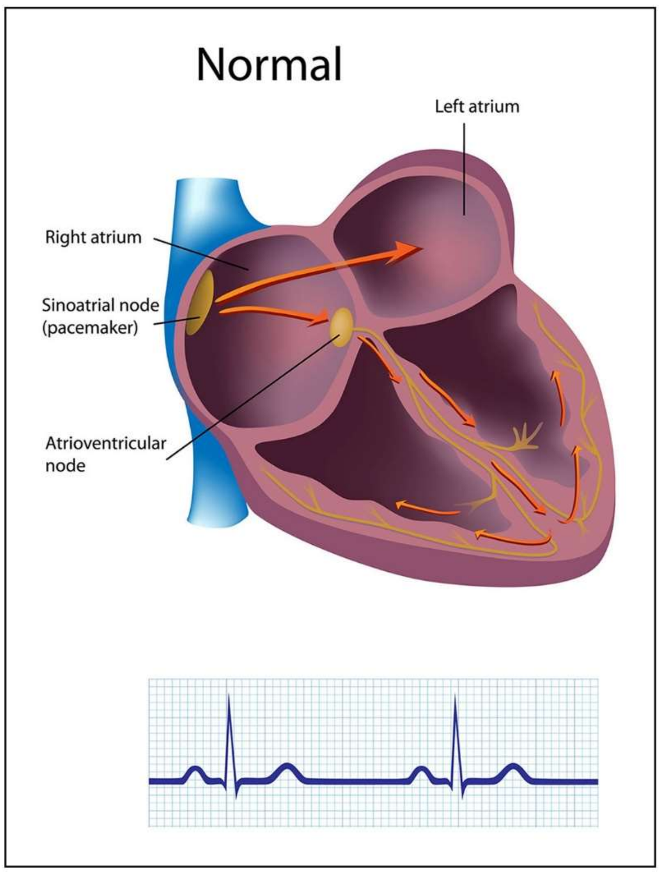

Figure 4: "The generation of the electrocardiogram. Credit: Alila Sao Mai/Shutterstock.com"[19]. Image adapted from[19].

1.3.2. The autonomic nervous system: sympathetic vs. parasympathetic

The human nervous system has two main components, the central nervous system (spinal cord and the brain) and the peripheral nervous system (the nerves that carry impulses to and from the central nervous system). One of the peripheral nervous system components is the autonomic nervous system (ANS). The ANS regulates visceral function, i.e., internal organs functions such as the heart and stomach. The function of ANS is reflexive and involuntary, e.g., the beating of the heart, contraction, or expansion of pupils[20].

The cardiac ANS can be divided into two components, extrinsic and intrinsic[21].

(1) Extrinsic: consists of fibers that mediate the connection between the heart and the nervous system.
(2) Intrinsic: comprises primarily autonomic nerve fibers in the human heart[22].

The two subdivided components of the extrinsic cardiac ANS are sympathetic and parasympathetic systems[22] (Table 1).

Table 1: Sympathetic and parasympathetic systems.

Source	System	Function	Response	E.g.
[20]	Sympathetic	Control body reaction when the human perceives threat or danger.	"fight or flight"	Dilation of pupils in the eyes, increased heart rate, and contraction of muscles.
	Parasympathetic	Predominantly control body activity when the body is relaxed or at rest.	"rest and recovery"	Decreasing the heart rate, constriction of pupils in the eyes, and relaxation of muscles.

1.3.3. Heart rate as a reliable biomarker

A main cardiovascular center, located in the medulla of the brainstem, integrates sensory information from the heart, limbic system, and cerebral cortex. It adjusts heart rate via switching the relative balance between parasympathetic and sympathetic systems to respond to sensory and higher brain center input[23]. Therefore, heart rate mediates the correlative activity of the sympathetic and parasympathetic systems[19].

With the development of modern signal processing in the 1970s, the investigation of the heart's complex rhythm increased quickly. The research demonstrates that heart rate fluctuations result from complex, non-linear interactions between different physiological systems[24]. Heart rate variability (HRV), which changes the time intervals between adjacent heartbeats, has been influenced by the interactions between blood pressure, respiratory control systems, and autonomic neural activity. The interactions produce short-term rhythms in HRV measurements[25–27]. Hence, HRV is considered a biomarker of neurocardiac function that demonstrates heart-brain interactions and ANS dynamics. HRV is necessary for interdependent regulatory systems that operate at different time and frequency scales to adapt to challenges[19].

1.3.4. Connection between cognitive flexibility, moral decision-making, and physiological signals

It has been established that spontaneous pupil size variations are reliable dependent variables in psychological research as an index of autonomic activation in ANS. Studies show that psychological manipulations of cognitive load, difficulty, fear, arousal, conflict, effortful decisions, and surprise all-cause increases pupil dilation[28–32].

The literature suggested that cardiovascular activity has effects on cognitive performance and perception. The intrinsic cardiac nervous system can affect activity in the motor cortex, affecting attention level, perceptual sensitivity, and emotional processing[19,33–36]. Thayer et al. (2012) proposed a connection link between executive functions and HRV. They showed the functional capacity of the brain structures in charge of working memory and emotional and physiological self-regulation, as indicated by HRV[37].

In the realm of morality, some studies suggest that individuals with higher HRV are more sensitive to aversiveness and are more concerned with others' welfare. They show more responsiveness to other needs than individuals with lower HRV[38–40].

To sum up, HRV reflects the balance between sympathetic and parasympathetic systems. In the ANS activity, a shift toward parasympathetic dominance can be detected by increased HRV, and decreased HRV reflects a relative increase in sympathetic activity. Supporting this standpoint, performance on various cognitive tasks can be successfully predicted by HRV[41], particularly tasks that require flexible cognitive control[42,43].

2. State of the art

2.1. Cognitive flexibility

Cognitive flexibility is an effective parameter in the decision-making process. A study demonstrates that participants with high cognitive flexibility performed better on decision-making tasks than participants who were less cognitively flexible[44]. Another piece of the literature shows that patients with major depressive disorder have a poor performance in changing circumstances. Due to the lack of sensitivity adjustment, they could not detect the advantage of choices in the sense of reward and punishment. Hence, they show poor decision-making behavior in static and dynamic environments[45].

Recent research studied the relationship between HRV and cognitive flexibility. They conclude that individuals with higher resting-state HRV in both time and frequency domain indexes demonstrate a higher level of flexibility (i.e., decreased switch cost) than participants with lower resting-state HRV[42].

One of the main aspects that can influence cognitive flexibility is the lack of attention. According to studies, pupil dilation is one of the reliable biomarker signals used as an attention index. There is a positive correlation between attentional load and increasing pupil sizes[46].

2.2. Moral Decision-Making

In a recent study on decision-making in the moral dilemmas of autonomous vehicles, an autonomous vehicle must sacrifice either an innocent pedestrian or its passenger; participants decide to sacrifice the passenger instead of the pedestrian due to the deontological approach based on their intuition. The study shows that people‘s decisions in a moral dilemma can vary due to two moral decision-making biases: personal perspectives and time restrictions.

(1) **Personal perspective**: participants see the scenario from two points of view: one from a passenger’s perspective and the other from pedestrians’. Participants protect the lives of the perspective from which they see the

scenarios, i.e., the decision has been changed to sacrificing a pedestrian instead of the passenger and vice versa.

(2) **Time restriction**: in the same scenario with a different time limit for participants to decide, the fewer times people were permitted to decide, the more their decision shifted to the deontological moral doctrine. On the other hand, once they are not under time pressure, they lean toward the utilitarian approach[47].

Another study about these two classic approaches in moral philosophy demonstrates supporting evidence about a positive correlation between empathic concern and deontological inclinations without any effect on utilitarian inclinations. Moreover, it showed a negative correlation between cognitive load and utilitarian inclinations, while deontological inclinations were unaffected. The findings support the independent contributions of these two approaches in moral judgments[48].

Some experiments demonstrated another factor influencing our judgments in a moral dilemma. The studies showed a relationship between participants' characteristics (e.g., a specific cultural group) and the people on the tracks significantly influencing individuals' choices[49–51].

In a study among healthy individuals (67 males), moral rule adherence was evaluated via a self-report measure of moral rule adherence (Ethical Position Questionnaire, EPQ[52]). Their integration abilities underlying the neural and physiological processes were assessed with HRV. The questionnaire is included moral idealism and moral relativism.

(1) **Moral idealism**: “refers to strict rule following that precludes the violation of moral rules in all circumstances.”
(2) **Moral relativism**: “refers to flexible rule following that allows the violation of moral rules in some circumstances.”

Their finding shows that individuals with higher HRV follow moral rules to a greater extent (i.e., in all circumstances) than individuals with lower HRV[53].

Behavioral studies replicate the result of questionnaire studies in a moral dilemma using a virtual environment. the research demonstrates that a virtual reality simulation is a promising tool for studying individuals’ choices in trolley problems[54,55].

We review the findings and methods of some experiments that have been executed in the context of moral decision-making, which use virtual environments to create a moral dilemma in their experiments (Table 2):

Table 2: Experiments summaries in moral decision-making, using a virtual environment

Source	Method	Findings
[56]	"We employed immersive virtual reality to assess ethical behavior in simulated road traffic scenarios, and used the collected data to train and evaluate a range of decision models. In the study, participants controlled a virtual car and had to choose which of two given obstacles they would sacrifice in order to spare the other. We randomly sampled obstacles from a variety of inanimate objects, animals and humans."	• The model comparison shows that "simple models based on one-dimensional value-of-life scales are suited to describe human ethical behavior in these situations." • In the severe time pressure effect on the decision-making process, they found that it declines consistency in the decision patterns. • "Demonstrates the suitability of virtual reality for assessing ethical behavior in humans, delivering consistent results across subjects while closely matching the experimental settings to the real-world scenarios in question."
[57]	An empirical study used a virtual environment to research what factors people recognize as relevant in driving situations. "The study put subjects in several "dilemma" situations, designed to isolate different and potentially relevant factors. They put subjects in the	• "Subjects showed a surprisingly high willingness to sacrifice themselves to save others, took the age of potential victims in a crash into consideration, and were willing to swerve onto a sidewalk if this saved more lives."

	position of making choices between two lanes on which their vehicle drove at a constant speed. The test subjects drove along different roads until obstacles emerged on both lanes, upon which they had four seconds to switch the lane they were driving on (or not), finally hitting a person."	
58	"We conducted a set of experiments in which participants experienced modified trolley dilemmas as the driver in a virtual reality environment. Participants had to make decisions between two discrete options: driving on one of two lanes where different obstacles came into view. Obstacles included a variety of human-like avatars of different ages and group sizes. Furthermore, we tested the influence of a sidewalk as a potential safe harbor and a condition implicating a self-sacrifice."	• "Results showed that subjects, in general, decided in a utilitarian manner, sparing the highest number of avatars possible with a limited influence of the other variables. Our findings support that people's behavior is in line with the utilitarian approach to moral decision making."
59	"To further understand the ethical issues of introducing self-driving cars, we conducted two moral judgement studies investigating potential differences in the moral norms applied to human drivers and self-driving cars. In the experiments,	• "Human drivers and self-driving cars were largely judged similarly. However, there was a stronger tendency to prefer self-driving cars to act in ways to minimize harm, compared to human drivers. "

	participants made judgements on a series of dilemma situations involving human drivers or self-driving cars. We manipulated which perspective situations were presented from in order to ascertain the effect of perspective on moral judgements."	• "There was an indication that perspective influences judgements in some situations. Specifically, when considering situations from the perspective of a pedestrian, people preferred actions that would endanger car occupants instead of themselves. However, they did not show such a self-preservation tendency when the alternative was to endanger other pedestrians to save themselves. This effect was more prevalent for judgements on human drivers than self-driving cars. "

2.3. Biomarkers

Other factors that correlate with executive functions are physiological aspects, such as heart rate. Recent advances in the realm of Psychophysiology tried to explain the interaction of two robust networks in the human body: the nervous system and the cardiac cycle. One model that attempts to achieve this target is the neurovisceral integration model. This complex systems model explains how HRV relates to neural structures involved in cognitive performance. In the internal system regulation, the brain is in charge of visceromotor (controlling movements), neuroendocrine (interaction between the endocrine system and the nervous system), and behavioral responses, which are crucial elements for goal-directed behavior and adaptability and health. The neurovisceral integration model is proposed as an integrated system for the internal system regulation[60].

Some experiments have been executed in the context of moral judgment, decision-making, and cognitive flexibility that measured biomarkers (Table 3):

Table 3: Experiments summaries in the realm of moral judgment, decision-making, and cognitive flexibility with measuring physiological signals.

Source	Topic	Experiment	Findings
61	Moral judgment	Examined whether resting cardiac vagal tone (linked to the ability to regulate the parasympathetic influence on the heart to optimally respond to situational changes by adjusting heart rate, arousal, and attention[62]) is **associated with moral judgment** using a mix of moral dilemmas, mathematical modeling, and psychophysiological measures such as **HRV**.	• Lower resting HRV, a cardiac vagal tone index, is associated with outcome-based, utilitarian moral judgments.
63	Cognitive flexibility	**Measuring pupillary activity** in two voluntary task switching experiments with randomly changing reward magnitudes.	• "Baseline pupil diameter was generally higher following switch trials as compared to repetition trials." • "Pupil responded dynamically to the reward manipulation: Phasic cue- and target-locked pupil dilation was larger in the reward phase as compared to the non-reward baseline block." • "Phasic pupil dilation in the target interval was highest when reward prospect increased and lowest when reward prospect decreased, suggesting that motivational arousal fluctuates in sync with changes in reward expectation."

2.4. Research question and hypothesis

Cognitive flexibility is a vital factor in designing our behavioral strategy when we face a new situation; on the other hand, the way we make decisions in moral dilemmas will guide us in our daily lives. Thus, the relationship between these two components is essential in our life. To study this relationship, we need reliable indexes to respond to the situational demands, such as physiological biomarkers, which assist us in exploring this relationship from a physiological perspective.

Since there have been a few attempts to investigate the relationship between cognitive flexibility and moral decision-making, in this thesis, our main attempt is to bridge the gap via our research questions and hypotheses (Table 4).

Table 4: Research questions and hypotheses.

Number	Research question	Hypothesis
1	What is the relationship between cognitive flexibility and moral decision-making?	Participants with a higher level of cognitive flexibility have less consistency (defined as acting in the same way over time in their decision-making in moral dilemmas) than participants with low cognitive flexibility.
2	What is our physiological response to situational demands in a moral dilemma?	Participants with a higher level of cognitive flexibility will experience higher HRV when facing a moral decision-making task than participants with low cognitive flexibility.
3	Are we evaluating different moral contexts by applying the same moral rule?	We expected to observe higher pupil diameter during switching the tasks in participants who will report that they consider moral contexts differently.

3. Methods

3.1. Experimental setup

The experiment is conducted in a laboratory setting, using a computer with a keyboard, mouse, and screen.

The experiment had one task in common with another experiment (out of the scope of this thesis) and had the same participants for both experiments. Due to avoid biasing our studies, both experiments were executed in one setup—the whole experimental pipeline implemented in the Unity Engine. Due to the randomization and external experiment, each task has its own executable.

The participant's heart rate and pupil diameter are recorded with an Empatica E4 wristband and eye-tracker, respectively.

3.2. Participants

The study tested 22 participants, of whom 1 was excluded due to a Unity crash during the experiment; of the remaining 21 subjects, 12 were female, and 9 were male with 16 different nationalities. The participants ranged from 23 to 45 years old, with 28.28 years on average and a standard deviation of 5 years. All participants were tested with the same equipment.

3.3. Procedure

Our approach is a within-subject design; all participants did both tasks. Firstly, the participant's heart rate and pupil baseline are recorded for five minutes simultaneously with an Empatica E4 wristband and eye-tracker. Secondly, cognitive flexibility and moral decision-making tasks are executed in random order (Figure 5). The participants' HRV and pupils' behavior had recorded during the two tasks. The timespan of recording biomarkers was placed between 12 a.m. and 9 p.m.

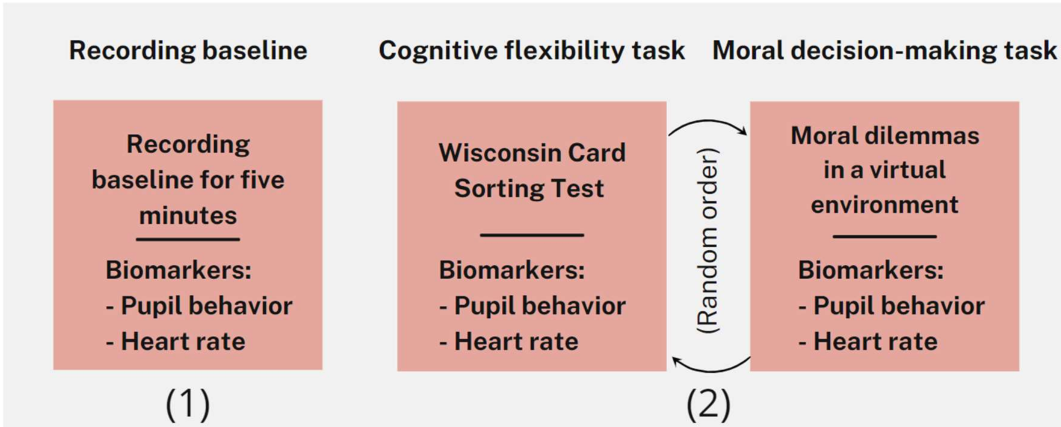

Figure 5: The experiment procedure

3.3.1. General consideration

Upon arrival, participants read and signed the informed consent in Unity Engine. Experimenters checked whether participants had prior trauma relating to mental and neuropsychological disorders or visual impairments. Before the experiment began, participants' heart rate and pupil diameter were recorded simultaneously for five minutes as a baseline when they were sitting and relaxed.

In order to keep experimenter-participants interaction to a minimum, the experimenter assisted the participant in putting on all the equipment and making sure they were put on correctly. The experimenter familiarized the participant with the control elements' essential functionality. Furthermore, participants were informed that experimenters could not observe their choices while performing the tasks. The participants were also informed how to abort the experiment if they wanted to quit the task. The process begins when the participant feels relaxed starting the experiment.

3.3.2. Measuring cognitive flexibility

One classic test that was first developed in 1948 to measure executive functions is The Wisconsin Card Sorting Test (WCST)[64]. The task is about set-shifting and abstract reasoning. Briefly, there are four cards with different characteristics of stimulus (shape, colors, and a number of objects) (Figure 6). The subject is asked to sort these cards based on other principles. The number of possibilities for the classification of the cards is four.

The experimenter provides feedback, correct or incorrect, about a given classification. The participants must learn from the feedback. After several cards have been sorted correctly, the experimenter will change the learned rule without informing the participant. There is difficulty in switching to the new rule for children younger than four years old and any participant with prefrontal damage. They continue the task with the previously learned rules[65].

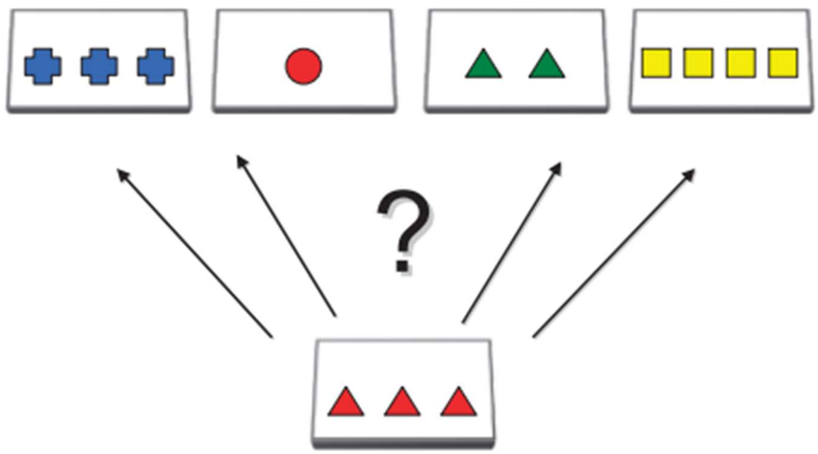

Figure 6: "Examples of tasks often used to assess executive function. In the Wisconsin Card Sorting Test (a), individuals must sort cards into one of four piles; each card has items on it that vary along three dimensions—color, number, and shape—with each dimension having one of four values (e.g., Color: red, blue, green, or yellow; Number: 1, 2, 3, or 4; Shape: circle, square, triangle, or cross). Individuals must deduce the correct rule (i.e., dimension) on which to sort the cards based on feedback provided by the examiner about whether each choice made was correct or incorrect"[65]. Image adapted from[65].

Cognitive flexibility had measured via the "bcst-64," a shortened standardized form of WCST. After ten consecutive correct responses, the rule will change; the task will be finished after completing 64 different stimulus cards. Participants did the task in the Unity Engine environment (Figure 7) and were informed that the task had ended by the program. For performance evaluation, the Heaton et al. (1993) method had used to score the WCST, perseverative responses, and perseverative errors to assess cognitive flexibility[66,67].

From a physiological standpoint, participants' heart rate and pupil behavior were recorded during the task to analyze later how these two biomarkers behaved when the rule changed. The experiment took fifteen minutes on average to complete.

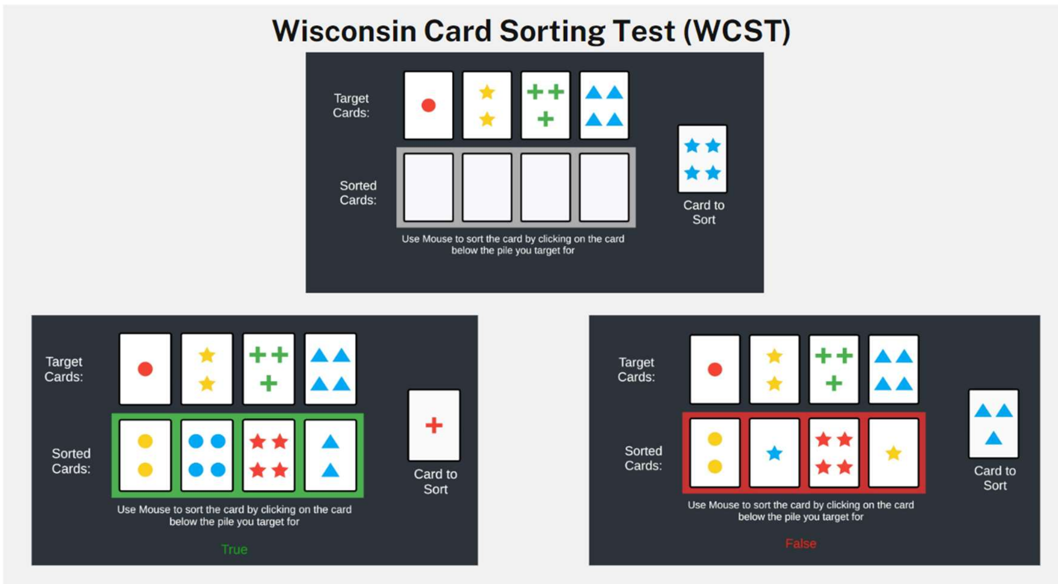

Figure 7: Screenshot from Unity implementation of WCST task.

3.3.3. Moral decision-making task

The detailed method design in the moral decision-making task is adapted from [54,56–59] and will be customized due to our approach and limitations.

Our participants did the task in the Unity Engine environment with a screen, mouse, and keyboard as a vehicle's driver, where they faced different trolley dilemmas in different contexts. The vehicle drives at a constant speed, and participants have four seconds to decide between two discrete choices: driving on one of two lanes where different obstacles come into view, including a combination of human-like avatars of different ages and group sizes, and finally hitting a person (Figure 8).

All practical instructions were provided within the Unity Engine implementation. Participants were informed that they were the only passenger in the car. They were also briefed about their limited control over the vehicle, i.e., they cannot modify the speed.

Participants could only navigate from one lane to another, and the car always aligned itself to the lane steered to. Participants were not mandated to act in any precise form.

Training trials were designed to familiarize participants with the vehicle's controls in the virtual environment; participants must successfully avoid objects, including control transition cycles. They must pass the training trial successfully; in case of failure, the training trial is repeated. After passing the training test three times successfully, the participants can continue to the main testing step.

In the main test, the participants were presented with five scenarios reported in detail below. In order to test our third hypothesis, we set our scenarios in a fixed order. After the second scenario, before the subjects moved to the next one, they faced a question about the similarity between the two previous scenarios. In each scenario, each subject went through the trials in a randomized order (also, the vehicle's starting point was randomized).

In order to avoid biases based on similarities, all characters were designed in a neutral style and characteristics. Also, to avoid biases based on gender, the avatars were all of the same genders as the participants. The participants' perspectives and range of vision will be the same in each trial.

All participants completed all of the various trials, and none of the trials were shown more than once. They were tested with the same equipment.

In order to have appropriate environments for the different experimental conditions, the participants could hear the vehicle sound effect of driving and break sound effect in case of collision. A fog-like curtain limited the participants' view to 55 m ahead while the vehicle moved at a constant speed of 36 kph (10 m/s). Subjects were driving along a short road period at some point and faced a critical situation. Each trial began from 160-200 m before the obstacles on the road (distance was kept random, preventing participants from predicting the precise moment they got clear eyesight of the challenging situation). The participants had 4 s (40 m) to decide up to 15 m before the potential collision. In order to prevent subjects from attempting to steer in between obstacles through insufficient lane-changing maneuvers, driving control was revoked at this point. In order to avoid a visual display of the collision, the screen was turned black five-meter before the collision. The screen remained black for two seconds until the subsequent trial began.

Our five scenarios are as follows:

(1) The classic trolley problem:

Consist of three trials, participants must decide between two lanes while driving—one person in one lane or another with 2, 4, or 6 people, respectively. We only presented standing adults as obstacles.

- 1 adult vs. 2 adults
- 1 adult vs. 4 adults
- 1 adult vs. 6 adults

(2) Egalitarian troubles:

The following five trials are concerned with problems of equality between different groups (influence of age). The participants were driven along a road, eventually facing two distinct individuals standing on the road, one on each lane. They need to choose between children and adults to hit.

- 1 child vs. 2 adults
- 1 child vs. 4 adults
- 1 child vs. 6 adults
- 2 children vs. 4 adults
- 2 children vs. 6 adults

(3) Sidewalks and people on the street:

It consists of five trials. The participants were driven along a one-lane road toward a group of adults with size divergences between one and six. The only way to save the group is to change lanes, drive on the sidewalk, and hit persons.

- 1 adult on the sidewalk vs. 2 adults on the street
- 1 adult on the sidewalk vs. 4 adults on the street
- 1 adult on the sidewalk vs. 6 adults on the street
- 2 adults on the sidewalk vs. 4 adults on the street
- 2 adults on the sidewalk vs. 6 adults on the street

(4) Self-sacrifice:

It consists of three trials. The participants were driven along a one-lane road toward a group of adults (varying in size between one and four). The only way to save the group is to change lanes and drive toward the stone road block posts, risking their own life.

- Self vs. 1 adult
- Self vs. 2 adults
- Self vs. 4 adults

(5) Self-sacrifice with an adult passenger in the car:

It consists of three trials. The participants had an adult passenger in the car. They were driven along a one-lane road toward a group of adults (varying in size between two and six). The only way to save the group is to change lanes and drive toward the stone road block posts, risking their own life and an adult passenger in the car.

- Self + 1 adult vs. 2 adults
- Self + 1 adult vs. 4 adults
- Self + 1 adult vs. 6 adults

From a physiological standpoint, participants' heart rate and pupil behavior were recorded during the task to analyze later how these two biomarkers behaved when the participants faced the forced-choice task, and the contexts of moral dilemmas changed. Their pupils' behavior was compared with their reports in the sense of similarity of these different moral contexts. The experiment took fifteen minutes on average to complete.

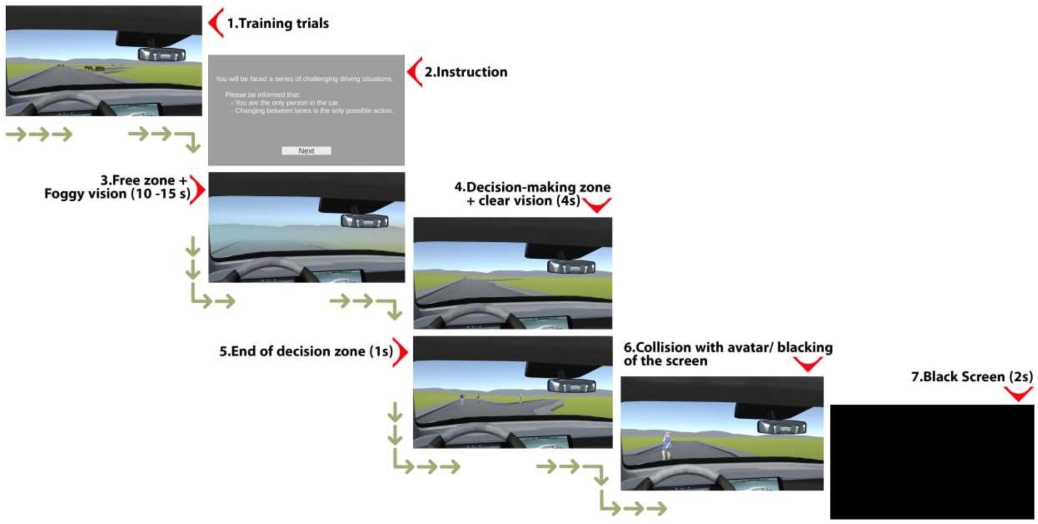

Figure 8: Screenshots from Unity implementation of moral decision-making task.

3.4. Equipment

(1) Empatica E4: for each participant, Blood Volume Pulse (BVP) was recorded via Photoplethysmography (PPG) sensors, which later allowed us to compute the participant's heart rate variability (Figure 9).

An E4 bracelet is worn like a wristwatch and is utilized to measure physiological signals such as BVP. The PPG sensor is embedded in the device: on the bottom side.

The technical information based on the Empatica E4 user manual about the sample recorded is as follows:

- "Sampling frequency 64 Hz (Non-customizable)."
- "LEDs: Green (2 LEDs), Red (2 LEDs) Photodiodes: 2 units, total 15.5 mm 2 sensitive area."
- "Sensor output: Blood Volume Pulse (BVP) (variation of volume of arterial blood under the skin resulting from the heart cycle)."
- "Sensor output resolution 0.9 nW / Digit."
- "Motion artifact removal algorithm: Combines different light wavelengths and tolerates external lighting."

Figure 9: Empatica E4 bracelet. The image is adapted from https://www.empatica.com/research/e4/

(2) Pupil Core headset: An adjustable eye tracker is used for gaze estimation, pupillometry, and egocentric vision research. It consists of three cameras, one World camera, and two adjustable Eye cameras (Figure 10). The world camera captures the subject's field of view, and the two Eye cameras detect the subject's pupil. We used 2d pupil detection to measure pupil size diameter.

Figure 10: Pupil Core headset. The image is adapted from https://pupil-labs.com/products/core/tech-specs/

4. Results

4.1. Relationship between cognitive flexibility and moral decision-making

Regarding our first hypothesis, we looked at the relationship between cognitive flexibility and participants' consistency in moral decision-making. On the one hand, we ranked our participants based on each person's sum of the number of perseverative errors in the WCST task for cognitive flexibility. On the other hand, we looked at the number of decisions between the deontological and utilitarian approaches in the moral decision-making task.

We removed one participant's data due to the Unity program crashing during the moral decision-making task.

4.1.1. Consistency in moral decision-making vs. Cognitive flexibility

Our data was distributed non-normally; hence the results were analyzed using the Spearman correlation coefficient. Although no statistically significant outcomes were obtained (Spearman correlation = 0.33, p-value = 0.14), there is a trend within the graph consistent with our hypothesis (Figure 11). The graph represents that participants who made fewer perseverative errors (indicating higher cognitive flexibility) in the WCST task had less consistency in their moral decision-making task.

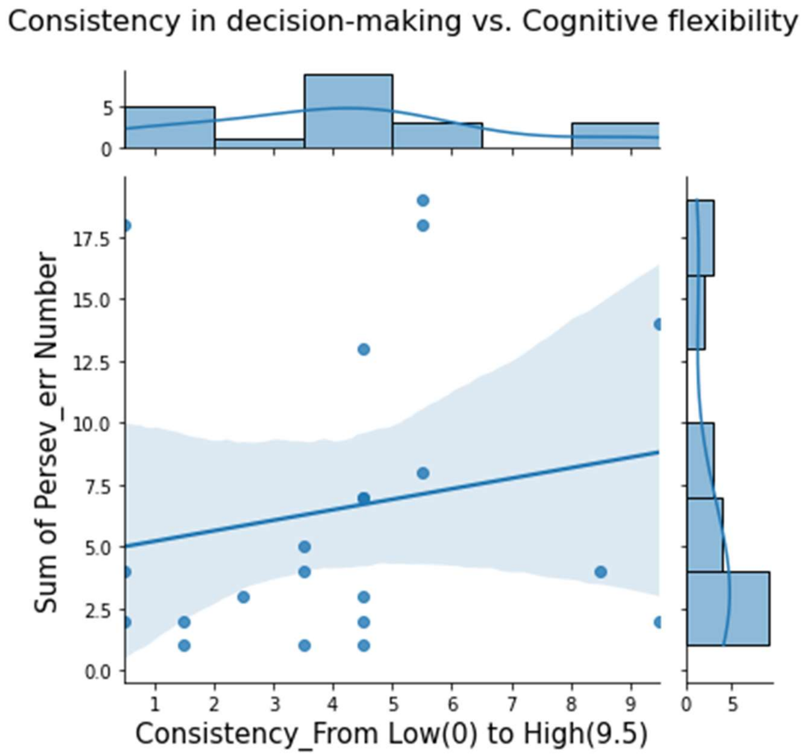

Figure 11: Cognitive flexibility vs. Consistency (variability between the deontological and utilitarian decisions) in moral dilemmas.

4.1.2. Moral decision-making ratio

We analyzed the number of moral decision-making ratios between utilitarian and deontological decisions (Figure 12). The boxplot shows an overview of the total decisions in which most decisions (median = 73.68%, and MAD = 7.80) are considered to save more lives than the deontological approach.

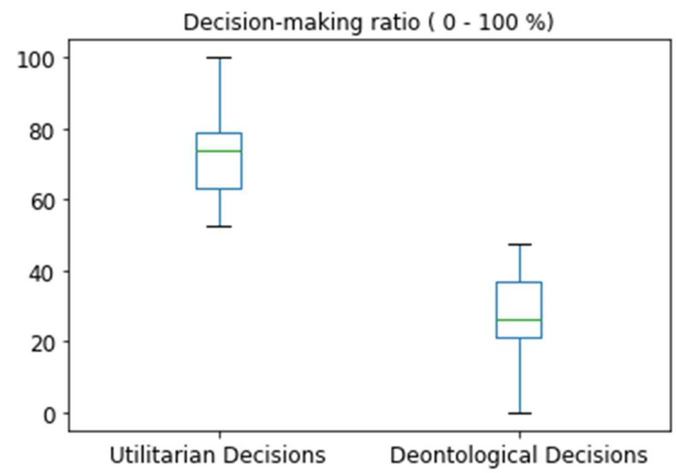

Figure 12: An overview of the number of moral decision-making ratios between utilitarian and deontological decisions in moral dilemmas.

Our data represent that the participants chose different approaches in different scenarios of moral dilemmas. For instance, in the classic trolley dilemma (Figure 13), participants chose the utilitarian approach over the deontological one (median = 100%, and MAD = 0.00). Nevertheless, in the egalitarian scenario (Adults vs. Children), the decisions support the deontological perspective than saving more lives (median = 60%, and MAD = 29.65) (Figure 14). However, we can see the tendency to save more lives (median = 80%, and MAD = 29.65) in the sidewalk scenario (Figure 15).

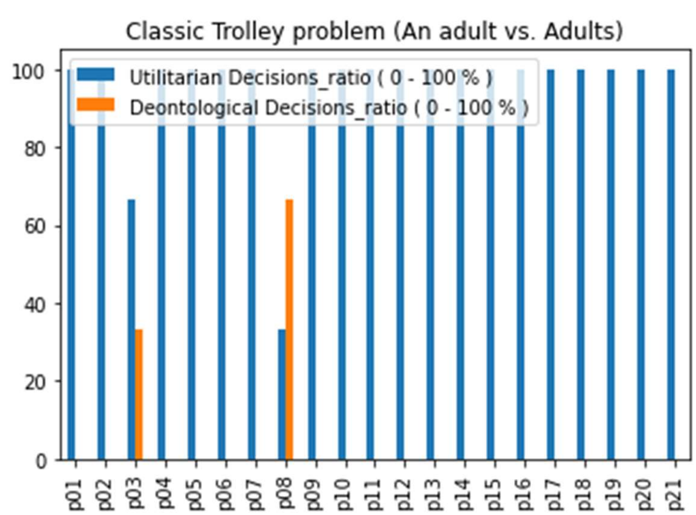

Figure 13: An overview of the number of moral decision-making ratios between utilitarian and deontological decisions in the classic trolley dilemma.

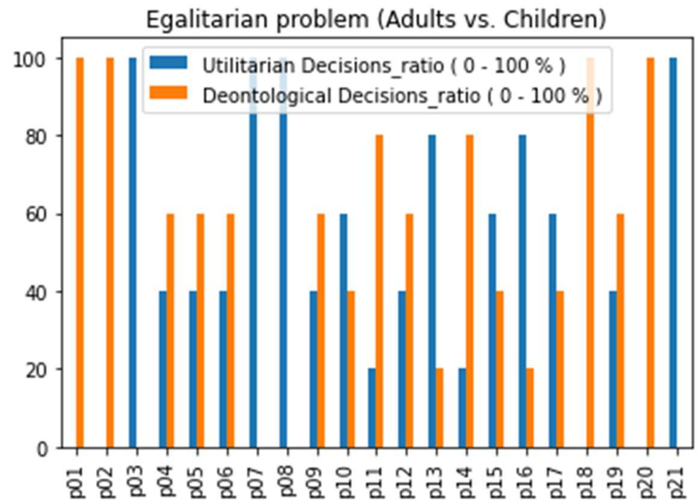

Figure 14: An overview of the number of moral decision-making ratios between utilitarian and deontological decisions in the egalitarian dilemma.

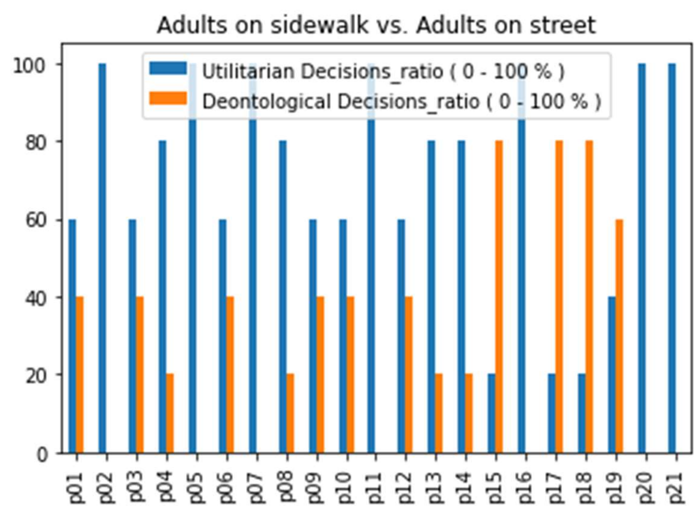

Figure 15: An overview of the number of moral decision-making ratios between utilitarian and deontological decisions in the sidewalk dilemma.

Although data analysis of both self-sacrifice scenarios shows that participants chose the utilitarian standpoint over the deontological perspective (median = 100%, and MAD = 0.0), we can observe slight changes in decisions toward the deontological approach in the context of self-sacrifice with an adult passenger in the car than when the subject is alone in the car (Figure 16 and 17).

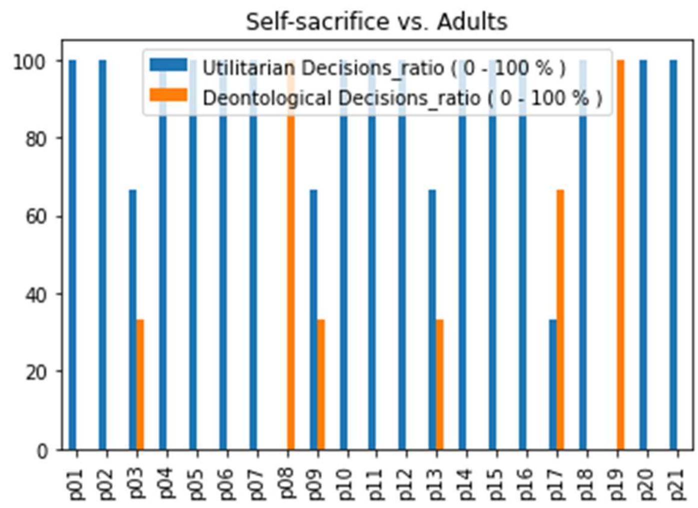

Figure 16: An overview of the number of moral decision-making ratios between utilitarian and deontological decisions in the self-sacrifice dilemma.

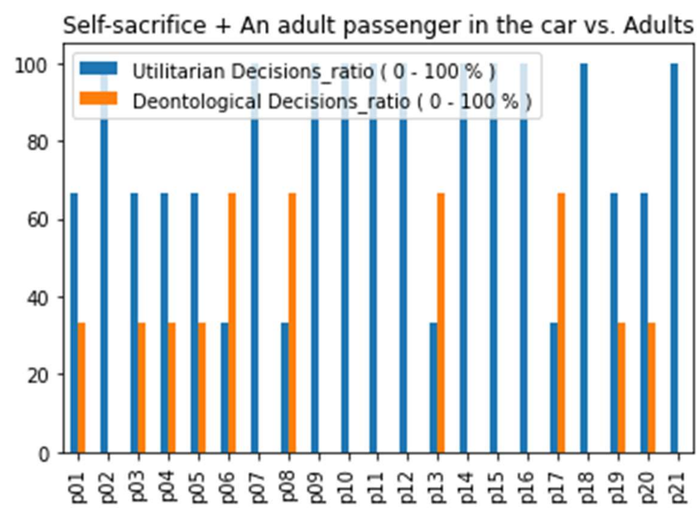

Figure 17: An overview of the number of moral decision-making ratios between utilitarian and deontological decisions in the self-sacrifice with an adult passenger in the car dilemma.

4.2. Relationship between HRV, cognitive flexibility, and moral decision-making

Regarding our second hypothesis, we looked at the relationship between HRV and cognitive flexibility when the subjects face moral dilemmas. The BVP data were synchronized and recorded using the lab streaming layer (LSL) and its lab recorder[68]. In order to preprocess the BVP data, the Neurokit2 library[69] was utilized, and then computed HRV based on the cleaned data. The root means square of successive differences between normal heartbeats (RMSSD) method was used for computing HRV.

The same method that was mentioned above was used to analyze cognitive flexibility. Also, the same approach was taken for the moral decision-making task.

We consider four participants' data as outliers because their HRV values were more outstanding than two times our sample's standard deviation.

4.2.1. Resting-state HRV vs. Cognitive flexibility

Firstly, we looked at the relationship between cognitive flexibility and resting state HRV. Our data distribution was not Gaussian; therefore, the results were analyzed using the Spearman correlation coefficient. The graph shows a trend consistent with our literature reviews, although the correlation was not statistically significant (Spearman correlation = -0.30, p-value = 0.23) (Figure 18). The graph represents that participants who made fewer perseverative errors (indicating higher cognitive flexibility) in the WCST task had higher resting state HRV.

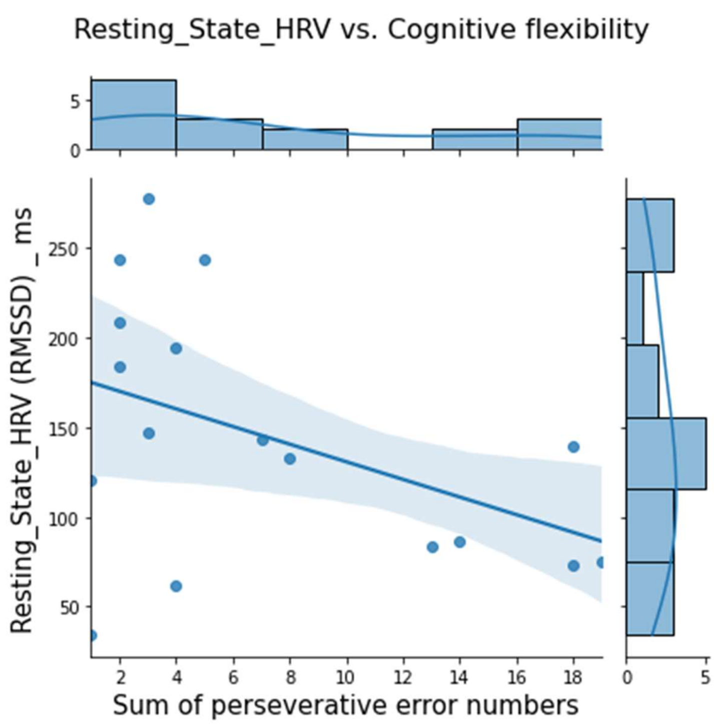

Figure 18: Resting state HRV vs. Cognitive flexibility.

4.2.2. Resting-state HRV vs. Consistency in decision-making

Secondly, we looked at the relationship between consistency in moral decision-making and resting state HRV. Our data distribution was not Gaussian; thus, the data were analyzed using the Spearman correlation coefficient. The graph shows a trend, although the correlation was not statistically significant (Spearman correlation = -0.28, p-value = 0.27) (Figure 19). The graph describes that participants with higher resting state HRV had less consistency in their moral decision-making task.

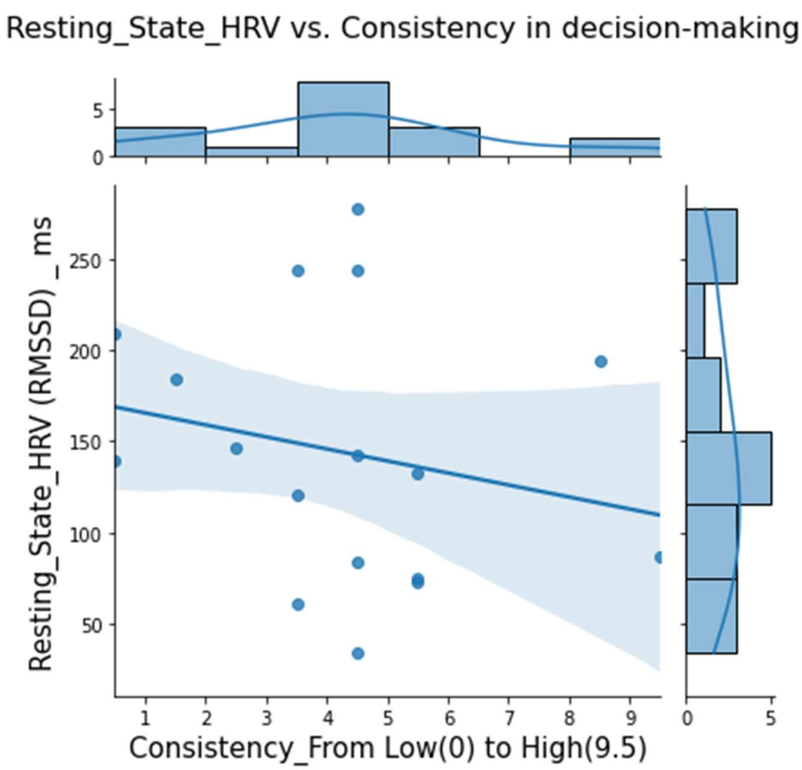

Figure 19: Resting state HRV vs. Consistency (variability between the deontological and utilitarian decisions) in moral dilemmas.

4.2.3. HRV in Moral decision-making vs. Cognitive flexibility

Lastly, we looked at the relationship between HRV behavior during the moral decision-making task and cognitive flexibility.

Due to taking into consideration of participants' HRV baseline for each subject, the difference value between resting state HRV and HRV for the moral dilemma task was used for checking this correlation. Our data distribution was not Gaussian; hence, the data were analyzed using the Spearman correlation coefficient. We could not find any specific trend (Spearman correlation = -0.32, p-value = 0.36) (Figure 20).

We had to remove five participants' data due to their noisy HRV and six subjects' data as outliers because their HRV values were more outstanding than two times our sample's standard deviation.

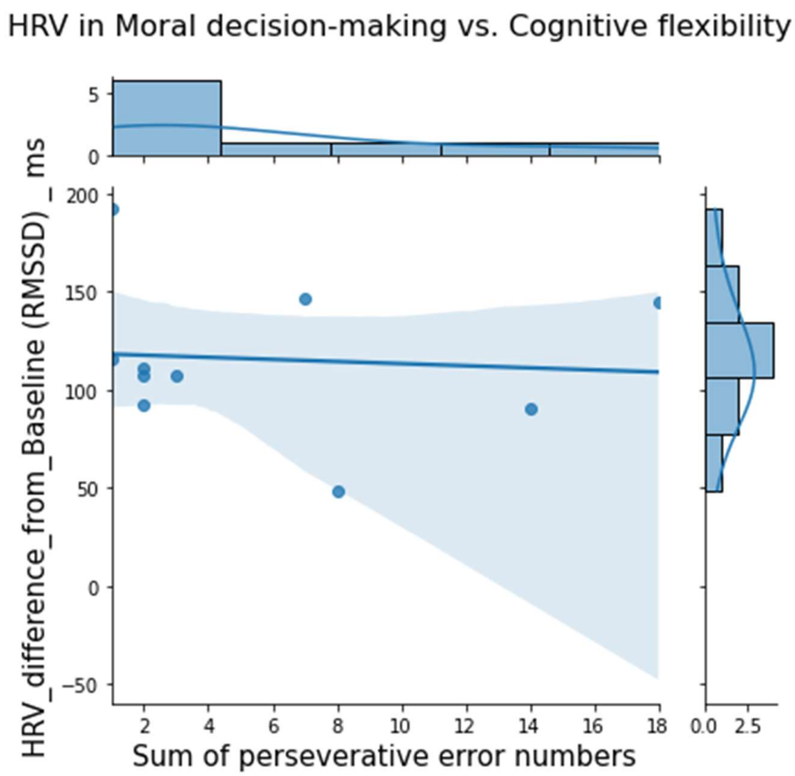

Figure 20: HRV behavior during moral decision-making task vs. Cognitive flexibility.

4.3. Relationship between pupil behavior and self-report evaluation

Regarding our third hypothesis, we looked at the relationship between pupil behavior and participants' self-reports about the similarity of different moral contexts in the moral decision-making task (0-Not at all to 10-Very). On the one hand, we had our participants' self-reports data on similarities between moral dilemmas. On the other hand, for synchronizing and recording pupil diameter, LSL was used. After preprocessing the pupil diameter data, the difference between the mean values of pupil diameter for each scenario was computed in the moral decision-making task to observe the pupil diameter changes while switching the scenarios. We removed eleven participants' data due to their noisy pupil recording data.

We used the Spearman correlation coefficient due to the non-normally distributed data. Although no statistically significant outcomes were acquired (Spearman correlation = 0.36, p-value = 0.27), there is a consistent trend with our hypothesis (Figure 21). The graph represents that those participants found moral dilemmas scenarios different from each other; their pupil diameter increased while switching the moral contexts.

Data analysis of our subjects' reports of to what degree they found moral scenarios similar to each other (0-Not at all, and 10-Very) are as follows (Figure 22):

- Classic trolley vs. Egalitarian: mean = 3.67 and SD = 1.58
- Egalitarian vs. Sidewalk: mean = 3.44 and SD = 3.00
- Sidewalk vs. self-sacrifice: mean = 1.88 and SD = 2.71
- Self-sacrifice vs. self-sacrifice + An adult passenger: mean = 4.57 and SD = 3.54

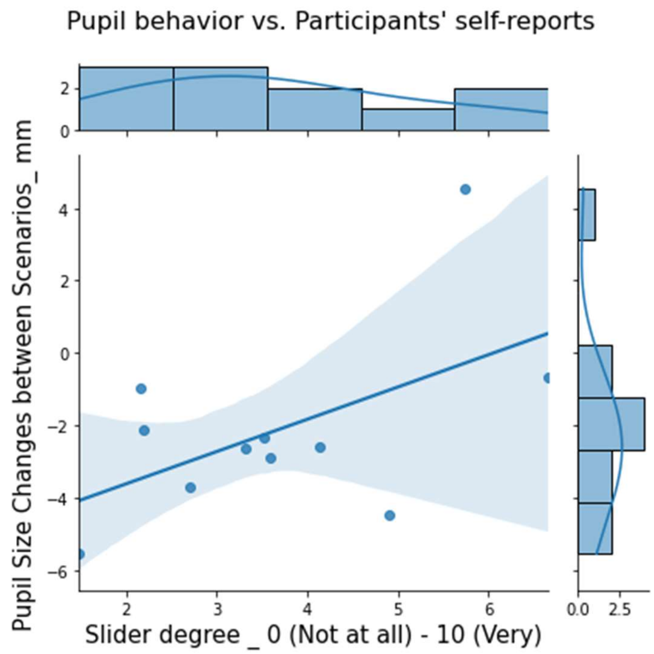

Figure 21: Pupil diameter changes while switching the moral scenarios vs. Participants' self-report on similarities between moral dilemmas.

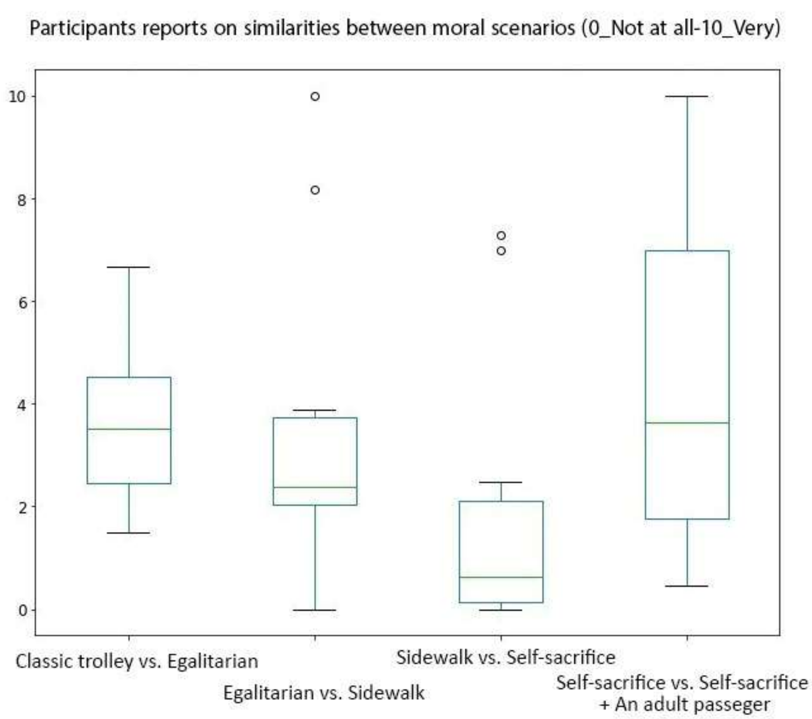

Figure 22: Participants' reports of to what degree they found moral dilemmas similar to each other (0-Not at all, and 10-Very).

5. Discussion and Conclusion

5.1. Discussion

Regarding our first hypothesis about the relationship between cognitive flexibility and moral decision-making, we found a positive correlation (not statistically significant) between cognitive flexibility and variability in the deontological and utilitarian decisions (Figure 11). Participants with higher cognitive flexibility consider various strategies for different moral contexts, so they switched between saving more lives and taking no action more than the subjects with lower cognitive flexibility.

In the classic trolley problem (an adult vs. several adults), the majority chose a utilitarian approach rather than taking no action. The most common strategy was mathematical reasoning (trying to spare as many people as possible), a kind of intuitive judgment. However, our subjects picked a deontological perspective than saving more lives when it comes to the adults vs. children dilemma. They considered the likelihood of injury in children more than in adults; hence, they saved children. Most subjects reported that they could not hurt children and that it is adults' responsibility to keep children safe.

In the sidewalk scenario, some participants noted that they evaluated the situation based on the number of people. However, having the same number of pedestrians on the sidewalk and the street, they decided to save the individuals on the sidewalk due to their right to be safe.

In the last two scenarios, self-sacrifice, most of our subjects noted that the number of people on the street had to outweigh the number of people in the car to choose the self-sacrifice option. Otherwise, they reported that it was not their fault that someone passed a street carelessly. Some participants assumed the likelihood of injury for car occupants was lower than for pedestrians; therefore, they chose the self-sacrifice alternative. Furthermore, a few subjects felt responsible for the passenger's safety in the car; thus, they did not take any action.

Regarding our second hypothesis concerning the relationship between HRV and cognitive flexibility when facing moral decision-making, a positive correlation (not statistically significant) has been found between resting state HRV and cognitive flexibility (Figure 18), These results are consistent with previous studies. The data analysis demonstrates that the participants with higher baseline HRV, feeling more relaxed in a resting state, made fewer errors in the WCST task than those with lower baseline HRV, which is consistent with our literature review[42]. Moreover, we saw a trend (not statistically significant) describing the subjects with higher baseline HRV switched between utilitarian and deontological approaches more than those with lower resting state HRV (Figure 19). We could not find any distinct tendency in our data concerning our hypothesis about the relationship between HRV changes during moral dilemmas and cognitive flexibility (Figure 20).

Lastly, concerning our third hypothesis, we compared our participants' reports with their pupil behavior when facing different moral contexts (Figure 21). A positive correlation (not statistically significant) has been noticed between the reports and pupils' diameter changes when they face a moral decision-making task. The trend is consistent with our hypothesis. The participants found moral dilemmas scenarios different from each other; their pupil diameter expanded while switching the moral contexts. An overall view of our participants' reports demonstrates that most of our subjects considered moral scenarios differently (Figure 22). The two most similar scenarios were the two self-sacrifice contexts, and the minor ones were sidewalk vs. self-sacrifice. For further suggestions and considerations for continuing the investigation in this research line, analyzing pupil dilation while the person is in the decision zone might be interesting. One of the standpoints to look at the pupil behavior in decision time can be comparing the mean value of pupil diameter changes in that decision time between the last trial of one context and the first of the following context.

Some of the issues that we faced in this study could be taken into account for continuing the investigation in this research line are as follows:

Firstly, we have an inescapable fact that time pressure made it difficult to gather an adequate sample size: therefore, our findings were derived from a modest number of individuals. Our sample size was quite international, which might affect the results in WCST if the aim is to compare their scores due to the average norm score for each country. More representative results might be achieved by conducting the study with a sufficient sample size focusing on one nationality. Secondly, room light and recording timespan may play the role of confounding variables and influence our biomarkers data collection. Moreover, age, gender, and habitual physical activity also affect heart rate. To overcome the issues regarding the recording timespan and room light, one solution might be executing the experiment in a specific short timeframe of the day for all participants. Furthermore, planning the experiment with two groups divided by gender might help to deal with the gender effect on physiological signals. Lastly, in choosing a biomarker for detecting physiological changes, we found pupil behavior more promising than HRV. Due to recording and computing HRV with different methodologies and the complexity of preprocessing physiological signals. One of the advantages of using pupil behavior as a biomarker can be that checking the participants' attention levels during our experimental tasks with pupil data is achievable, which is beyond this study's scope.

5.2. Conclusion

In summary, although none of our findings were statistically significant, a positive correlation was found between cognitive flexibility and moral decision-making variability in deontological and utilitarian methods, which was consistent with our hypothesis. Even though we found a positive correlation between resting state HRV and cognitive flexibility, no specific tendency has been seen between HRV changes when facing moral dilemmas and cognitive flexibility. A negative correlation is seen between resting state HRV and consistency in moral decision-making. The subjects with higher resting state HRV switched between deontological and utilitarian approaches more than those with lower resting state HRV. Another positive correlation has been noticed between pupil dilation changes and self-reports of participants in terms of finding various moral contexts similar to each other, which was consistent with our hypothesis.

Despite the study's limitations and not finding any significant values, this research contains great potential for enhancing our understanding of the link between these two essential aspects of daily life. These results have relevance to the study of the cognitive mechanisms underlying moral decision-making in particular, but also, overall, to the broader literature regarding how social norms and conventions are formed and maintained over time (Freire et al., 2020)[70].

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