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Kessel Run: exploring cooperative behaviours in a multiplayer BCI game

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"Deep in the human unconscious is a pervasive need for a logical universe that makes sense. But the real universe is always one step beyond logic."

Frank Herbert

Resumo

Apesar de terem como propósito original o restauro da função a portadores de deficiências motoras, as Interfaces Cérebro-Computador (BCI, do inglês *Brain-Computer Interface*) têm cada vez mais aplicações que vão para além de controlar o cursor de um computador ou mover uma cadeira de rodas. Com o recente avanço da tecnologia de electroencefalografia (EEG), cada vez mais portátil e económica, a investigação na área dos BCI tem nos últimos anos dado maior destaque às aplicações para utilizadores saudáveis, nomeadamente na área do entretenimento. BCI baseados em EEG estão gradualmente a ser mais usados até mesmo em jogos comerciais. Os videojogos do género multijogador são extremamente populares entre os jogadores, pelo que se torna bastante interessante olhar para os jogos multi-cérebro, isto é, jogos onde de uma ou outra forma a atividade cerebral de mais do que um utilizador é analisada e necessária para jogar o jogo.

Num outro tópico de investigação, as medições de EEG são também usadas por neurocientistas na pesquisa convencional dos processos de tomada de decisão e raciocínio estratégico. Um dos paradigmas mais frequentemente utilizados para estudar a tomada de decisão é o uso de dilemas da teoria de jogos jogados por uma ou duas pessoas. A teoria de jogos é aplicada a uma panóplia de áreas que vão desde a economia à psicologia, podendo naturalmente ser aplicável aos videojogos cooperativos ou competitivos.

Conseguiremos extrair novos conhecimentos acerca da neurociência da tomada de decisão a partir de jogos BCI multijogador? E, por exemplo, será possível manipular a estratégia de um jogador fornecendo-lhe informação sobre o que vai na mente dos seus adversários?

O objetivo desta dissertação é explorar os comportamentos cooperativos que ocorrem entre jogadores num jogo BCI multijogador, bem como enquanto jogam dilemas clássicos da teoria de jogos. Ao investigar medidas neurológicas correlacionadas com o raciocínio estratégico tais como os potenciais evocados (ERP, do inglês *Event-Related Potentials*) durante decisões cooperativas ou desertoras, procuramos aplicar os conhecimentos da pesquisa em tomada de decisão aos jogos digitais de classe comercial.

Numa primeira etapa deste trabalho, foi desenhado e implementado um jogo BCI cooperativo baseado no paradigma SSVEP (do inglês *Steady-State Visually-Evoked Potential*) chamado *Kessel Run*. No jogo *Kessel Run*, dois jogadores devem trabalhar juntos de forma a pilotar uma nave espacial através de um campo de asteroides. O objetivo do jogo é finalizar uma corrida de 2 minutos sem perder todo o combustível, desviando-se de obstáculos e recolhendo bónus. O paradigma de interação SSVEP foi implementado usando dois painéis LED externos, acoplados ao monitor, permitindo aos jogadores mover a nave para cima ou para baixo ao olhar para as luzes, a piscar a uma frequência de 15 e 12 Hz, respetivamente.

Dado que uma das nossas principais motivações era desenhar um jogo BCI que não fosse simplesmente uma prova de conceito da tecnologia, mas também divertido para os jogadores, foram seguidos os requerimentos para um bom design de jogo. Desta forma, o jogo *Kessel Run* apresenta regras e objetivos claros, mantendo-se desafiante para os jogadores, com o desafio adicional de controlar o BCI. Para além disso, de forma a proporcionar a experiência cooperativa adequada, os dois jogadores tinham funções interdependentes ditadas pelas mecânicas de jogo, uma vez que um jogador só consegue controlar um motor da nave, e esta só pode subir ou descer quando ambos os jogadores a controlam ao mesmo tempo. Para os ajudar a alcançar a vitória mútua, os jogadores podem comunicar verbalmente para antecipar obstáculos e melhor controlar o jogo.

Na segunda etapa deste trabalho, foi desenhado o jogo *Dilemmas*: um conjunto de cinco dilemas sociais iterados habitualmente utilizados na teoria de jogos. Em cada jogo, os jogadores enfrentam uma escolha entre duas opções: cooperar com o outro jogador ou desertar. A combinação de ambas as decisões resulta num de quatro desfechos possíveis, cada um com diferentes consequências para cada jogador, representados por uma pontuação numérica. Para cada jogo, um jogador ganha uma ronda quando recebe mais pontos do que o adversário, mas os jogadores tanto podem tentar maximizar a sua pontuação pessoal para derrotar o adversário como tentar maximizar a pontuação do grupo ao tomar decisões que beneficiam ambos os jogadores igualmente.

O jogo *Dilemmas* tem o propósito de servir como um ambiente controlado que nos permita recolher dados da atividade cerebral durante decisões cooperativas e desertoras. Os participantes tomam as suas decisões recorrendo ao teclado e não há qualquer comunicação permitida, como a finalidade de reduzir artefactos devidos ao movimento e ruído no sinal. Foram analisados os ERPs no sinal de EEG marcado no tempo no momento que antecede a tomada de decisão e após a apresentação do desfecho de cada ronda do jogo.

Após implementar ambos os jogos, foi preparada uma experiência onde 12 participantes (em 6 pares) foram convidados a usar toucas EEG enquanto jogavam *Kessel Run*, seguido de *Dilemmas*. A performance do BCI durante o *Kessel Run* foi calculada através de uma sessão de treino antes do jogo começar. A experiência de jogo e social dos participantes foi também estudada, com recurso a questionários validados preenchidos após cada sessão de jogo. Foi realizada a análise da atividade cerebral registada durante ambos os jogos, onde foram estudados os ERPs com origem no córtex medial frontal, nomeadamente as componentes P300 e a negatividade relativa a feedback (FRN, do inglês *Feedback-Related Negativity*).

A performance do paradigma SSVEP no BCI foi mais baixa do que o esperado, alcançando apenas uma precisão máxima de 79% como precisão média geral de 55% para um nível de chance de 33%. Os dois fatores identificados que mais influenciaram este resultado foram a variabilidade na deteção da frequência de SSVEP entre sujeitos e a falta de escuridão na sala. A maioria dos participantes obteve piores resultados de classificação para a frequência de 15 Hz do que para 12 Hz, possivelmente devido a 12 Hz pertencer à banda alfa dominante. Embora funcione como prova de conceito para um jogo SSVEP multijogador, um paradigma mais intuitivo como o movimento imaginado pode ser mais adequado para o *Kessel Run*, permitindo aos jogadores manter o olhar no ecrã.

A experiência reportada pelos jogadores foi de forma geral positiva, apesar da dificuldade em controlar o jogo com o paradigma SSVEP. Os jogadores não se sentiram muito competentes durante o jogo, mas de qualquer maneira atingiram um estado de Flow. Isto pode dever-se à estratégia colaborativa desenvolvida por alguns jogadores para contornar a má classificação SSVEP, em que o jogador com melhor controlo controlava a nave enquanto o companheiro dava direções. Na avaliação da presença social, os jogadores reportaram que empatizaram com o outro, em parte devido à necessidade de comunicar para ganhar o jogo. Dado que os jogadores se sentiram inclinados a trabalhar com o outro, podemos dizer que as regras de design de jogo cooperativo foram implementadas com sucesso e o jogo proporcionou uma experiência social positiva.

No jogo *Dilemmas*, a presença social reportada pelos jogadores foi ligeiramente diferente, resultado da natureza contrastante do jogo. Neste jogo, o nível de familiaridade dos dois participantes em cada sessão influenciou fortemente a forma como jogaram. Participantes emparelhados com um desconhecido sentiram-se menos inclinados a cooperar, e tomaram uma abordagem mais competitiva ao jogo, sentindo menos empatia pelo outro. Os jogadores reportaram também mais sentimentos negativos durante o *Dilemmas* do que durante o *Kessel Run*, embora tal se deva talvez às rondas perdidas e não à interação com o companheiro. A estratégia *tit-for-tat* (olho por olho) foi a mais adoptada pelos jogadores, o que significa que começavam por cooperar e subsequentemente replicavam a decisão feita pelo adversário na ronda anterior.

No que respeita ao estudo de ERPs durante o jogo, começou por se analisar os dados recolhidos durante o *Kessel Run*. Os registos acabaram por ser demasiado ruidosos para se extrair alguma informação sobre os potenciais que antecedem a tomada de decisão. As mecânicas e comandos do jogo não favoreceram a recolha de dados EEG para esta análise, uma vez que os jogadores eram encorajados a falar e mover a cabeça para olhar para as fontes de luz de forma a controlar o jogo. A implementação de um paradigma de interação passivo pode possibilitar este estudo num jogo BCI.

Por outro lado, foram identificadas com sucesso duas componentes ERP marcadas no tempo em relação à apresentação do desfecho no jogo *Dilemmas*: o P300 e a FRN. O ambiente mais controlado deste jogo facilitou a deteção de uma forte positividade na região medial frontal, para os canais Fc1, Fc2, Fz e Cz. Esta positividade corresponde às características da componente P300, uma deflexão positiva no ERP, relacionada com o processamento de informação acerca de ganhos e perdas. O P300 foi observado entre 200 e 500 ms após a apresentação do desfecho dos jogos aos jogadores. A componente FRN foi também detetada, embora apenas nos ensaios em que os jogadores cooperaram e perderam nessa ronda. A FRN foi identificada de 200 a 250 ms após o estímulo visual (desfecho), correspondendo a situações em que os jogadores adotaram a estratégia *tit-for-tat*, particularmente comum entre participantes que não se conhecem. Um jogador que coopera e recebe um desfecho negativo (perde a ronda) tem maiores probabilidades de desertar na ronda seguinte, repetindo o comportamento prévio do adversário.

Os resultados alcançados neste trabalho ajudam-nos a compreender a dificuldade em adquirir dados EEG durante uma experiência de jogo BCI ativa. Para atingir uma deteção adequada de ERPs durante um jogo, é necessário desenvolver algoritmos mais robustos de forma a ultrapassar a presença de artefactos. Todavia, as aplicações dos correlatos neuronais de tomada de decisão em jogos parecem promis-

soras, sobretudo em jogos sérios e jogos multijogador.

Palavras-chave: Interface cérebro-computador; Tomada de decisão; Colaboração; Videojogos; Multijogador.

Abstract

Traditional brain-computer interface (BCI) research has recently turned to applications for healthy users, such as games. Because electroencephalography (EEG) is a cheap, portable and popular way of accessing brain activity, EEG-based BCIs are gradually being more used even for commercial games. Multiplayer games are immensely popular among gamers, so it becomes interesting to look at 'multi-brain games', that is, games where in one or other form the measured brain activity of more than one user is needed to play the game. On a different research topic, EEG measures are also used by neuroscientists in traditional decision-making and strategic reasoning research. One of the most common paradigms used to study decision-making is to use game theory dilemmas played by one or two persons. Game theory is applied to a myriad of areas from economics to psychology, and can of course be applicable to cooperative or competitive video games.

The goal of this dissertation is to explore the cooperative behaviours that happen between players in a multiplayer BCI game, as well as while playing classic game theory dilemmas. By looking at neural correlates of strategic reasoning such as event-related potentials (ERPs) during cooperative or defective decisions, we will try to bring decision-making research and insights to commercial grade digital games.

We have divided this work's methodology into two parts: firstly, an original two-player cooperative BCI game (*Kessel Run*) controlled with steady-state visually-evoked potentials (SSVEP) was conceptualized and developed; secondly, a non-BCI game inspired by iterated social dilemmas was also developed. We have designed and set-up an experiment where participants played both games sequentially, and have collected EEG data during both gaming experiences, as well as the reported game experience and social presence from participant-filled questionnaires.

Despite a lower than expected accuracy in the BCI paradigm used to control the game *Kessel Run* (maximum of 79% and 55% on average), participants adjusted and developed strategies to successfully navigate a spaceship together in a virtual environment, reporting a positive game experience. Studying ERPs while playing *Kessel Run* proved ineffective, due to the fast pacing of the game and movement artefacts caused by the SSVEP paradigm.

However, in a more controlled setting like the game *Dilemmas*, we have successfully identified two components heavily linked to information processing and decision-making. A strong medial frontal positivity corresponding to the P300 component was observed between 200 and 500 ms after the presentation of game outcomes to the player. In trials where players cooperated and lost the round, the feedback-related negativity (FRN) was also detected, as would be expected when participants fail to achieve a desired feedback.

Designing a BCI game that employs the P300 paradigm might improve the success of merging decision-making neural correlates in a gaming experience. Nevertheless, the insights gathered in this study made us understand the difficulty of collecting EEG data during active BCI game play. Still, an interesting prospect would be to use a subject's particular brainwaves as a means to decode future decisions, and in that way improve collaboration in a game or team activity.

Keywords: Brain-computer interface; decision-making; cooperation; video games; multiplayer.

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Introduction

1.1 Context

For a long time now, the idea of interacting with machines only through thought has captured the human imagination. Even creating devices that can peer into a person's mind has only been object of myths and modern science fictions stories. It is only with the recent advances in cognitive neuroscience and brain imaging technologies that we get a sense of capability to interface directly with the human brain. This ability is made possible by using sensors that can monitor some of the physical processes that occur within the brain that correspond to certain forms of thought.

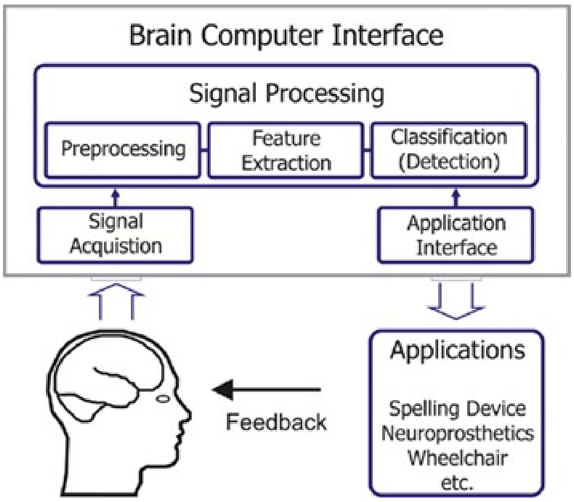


Figure 1.1: Schema of a Brain-Computer Interface (from [30]).

Mainly motivated by the needs of people with physical disabilities, researchers have used these technologies to build brain-computer interfaces (BCIs), communication systems that do not depend on the usual brain output pathways like peripheral nerves and muscles. In these systems, users may explicitly manipulate their brain activity instead of using motor movements that can be used to control computers or a variety communication devices (see Fig. 1.1) [30]. This work can have a really huge impact on the lives of those who suffer from devastating neuromuscular injuries and neurodegenerative diseases such as amyotrophic lateral sclerosis [36], which progressively erases individuals' muscular activity while leaving cognitive function unharmed.

During the last couple of years, BCI research has been moving into applications for healthy people. Reasons for this range from providing applications to increase user quality of life to the commercial benefits of such a large target group [47]. Among these applications for healthy users, the area of games particularly receives a lot of interest, as gamers are often among the first to adopt any new technology [52]. In addition, a large part of the general population plays games, even if only casually. Since these able users have many other interaction modalities at their command, they have a lot more requirements for such an interface than the people for which this is the only option to interact with the external world. Furthermore, in games we can use our imagination and can consent events in non-real-life situations, happening in virtual worlds. Games allow cooperation and competition with multiple and distributed users and implement interaction modalities and effects that are unusual but can be believable, depending on the design of the game.

1.2 Motivation and goals

Current BCI games are often just proofs of concept, where a single BCI paradigm is the only possible means of control, such as moving a paddle in the game Pong to the left or right with imaginary movement of the hands [35]. These BCIs are weak replacements for traditional input devices such as the mouse and keyboard: they cannot achieve the same speed and precision. Due to these limitations, there is still a large gap between these research games and the ones currently developed by the game industry.

On the other hand, the current trend towards a more natural interaction in games can be taken one step further with the BCI technology. Like our thoughts, computer games do not take place in the real world, and are not constrained to what is physically possible. Therefore, it would make sense to express ourselves directly in the game world, without mediation of physically limited bodily actions. The BCI can bypass this bodily mediation enabling the gamers to express themselves more directly, and more naturally given a game context.

Electroencephalography (EEG), the most widely used technology to implement BCIs is also commonly successfully used, together with game theory, in the investigation of the neural basis of social interactions and social decision-making. In particular, researchers are interested in what happens in the brain of subjects involved in games where each player can choose between cooperative and non-cooperative behaviours, with the aim of understanding the modification of brain activity related to the selected strategy [37].

Moreover, for some applications, instead of recognizing brain activity of one user and deciding how to use it, we can have recognition of brain activity of many collaborating users involved in the same task, or game. This multi-brain computer interfacing may lead to more reliable decisions and certainly it can lead to new and interesting applications of BCI. Knowing about a collective mental state of a group of users can also provide for interesting applications in game, entertainment and artistic installations. Being able to improve, in real time, decision processes by measuring and aggregating activity of all the brains of people involved in the decision making, as can be the case in multi-user games that allow the forming of teams makes it also possible to issue commands to a game as the result of unstable team brain activity.

The main goal of this work is to explore how neurophysiological measures of cooperation or defection from decision-making research can be implemented in a multiplayer BCI game. We intend to design an original, cooperative BCI game that is enjoyable for the players, following good game design requirements. User experience should be evaluated to determine how well the applied interaction paradigm suits the game developed. Additionally, we intend to observe what decision-making correlates are present in a time-locked EEG signal in order to categorise brain activity corresponding to cooperative game decisions.

1.3 Structure of report

This report is structured in the following manner: in chapter 2 the background concepts relevant to the present work are briefly explained. In chapter 3 some related work is described, on the studies on social decision making and recent multiplayer BCI games, and in chapter 4 the overall methodology for this work is described. Chapter 5 describes the design of both the BCI and dilemmas games as well as the tools used. In chapter 6 the set-up of the experiment performed is described. Chapter 7 presents the results of this experiment and in chapter 8 findings are discussed. Chapter 9 ends with the conclusion and possible future work.

2

Background

This chapter aims to give a brief explanation of brain-computer interfaces applied to games as well as game theory and how it is used to study decision-making.

2.1 Brain-computer interfaces and games

When it comes to measuring brain signals, there are two general classes of brain imaging technologies: invasive technologies, in which sensors are implanted directly on or in the brain, and non-invasive technologies, which measure brain activity using external sensors. Although invasive technologies provide higher temporal and spatial resolution, non-invasive techniques such as electroencephalography (EEG) are by far the most common in BCI research due to being inexpensive, portable, and safe devices. EEG uses electrodes placed directly on the scalp to measure the weak (5–100 μV) electrical potentials generated by activity in the brain [65].

BCI applications rely on brain signals originating from player actions and reactions to events. These actions and reactions are called interaction paradigms and are usually divided into three categories: mental state regulation, movement imagery and evoked response generation. BCI games can be categorized according to these three interaction modes.

In mental state regulation games players try to self-induce certain psychological states such as being relaxed, concentrated, stressed and so on. Most of the mental state games allow players to move physical [26] or virtual [51] objects but there are other uses such as changing the game avatar [52]. Movement imagery games are those in which players imagine doing bodily movements to navigate, as in driving a virtual car [35], or to make selections, as in playing *Pinball* [70].

While the first two categories result in games that use BCIs based on induced activations (i.e. the user can initiate actions without depending on stimuli from the game), evoked responses, on the other hand, require a tight coupling between the game that presents the stimuli and the BCI, since the application measures the response to a stimulus. This class of games is dominated by steady-state visually evoked potential (SSVEP) games, accompanied less frequently by P300 games [20].

2.1.1 SSVEP-based interaction

SSVEP is a brain response to flickering light or images. When we observe visual stimulus, say an image, that is constantly re-appearing at a frequency of f then the amplitude of the signals measured from our visual cortex are enhanced at frequency f and its harmonics ($2f$, $3f$, and so on). This way, if there is a single stimulus then we can understand whether someone is looking at it. If there are multiple stimuli, we can understand to which of them someone is paying attention.

One way of using SSVEP is to map the strength (amplitude) of SSVEP that is evoked by a single stimulus to game actions. For example, a weak SSVEP can steer a virtual plane to the left while a strong one to the right [43]. However, the most popular approach is to use multiple stimuli, each associated with a command. With this approach, BCI is usually used to select a direction, for example to steer a racing car (see Figure 2.1) [42]. With this method, a greater number of commands can be issued.

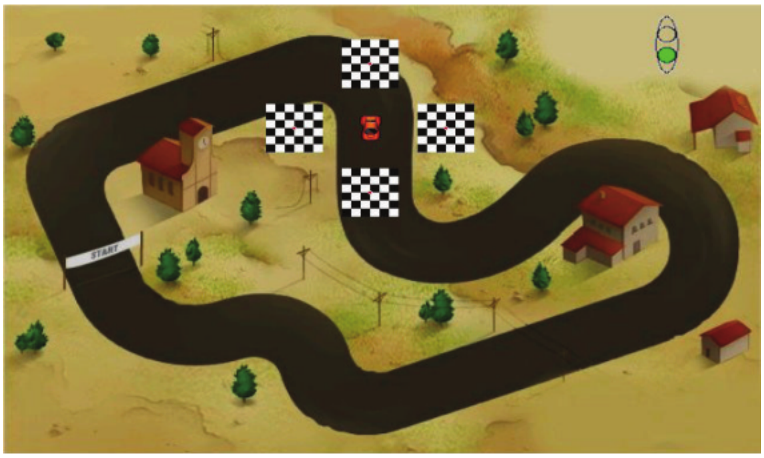


Figure 2.1: Four small checkerboards flickering at different but fixed frequencies move along with a navigated car. The subject is able to control the direction of movement of the car by focusing her/his attention on a specific checkerboard. (from [42]).

SSVEP detection usually involves a signal averaging process which increases signal-to-noise ratio (SNR) [16]. In a game, this requires the signal to accumulate for some time and introduces a delay. Therefore, it may not be the most suitable for fast games. On the other hand, this interaction mode is suitable for multimodal games thanks to its high SNR. Letting players control the game in combination with other controllers not only enables fast SSVEP games but increases the number of overall commands that can be transmitted to the game.

2.2 Towards Multi-brain Games

There are several kinds of applications where it is useful to know how people experience a certain event or product. This can be done by taking questionnaires, looking at facial expressions and also measuring (neuro-) physiological characteristics of the potential users. The latter may yield more reliable information than what can be obtained by asking or observing participants in an experiment. For example, brain activity from multiple persons can be measured and analysed for neuromarketing purposes: an example is neurocinematics [25], where similarities in spatiotemporal responses across movie viewers are studied. Real-time processing of such brain activity may in the future provide collective or individual decisions about the continuation of a movie while watching it.

There is certainly more research in which multi-brain activity is investigated, where the immediate goal is not yet real-time applications, but where these can be foreseen, even in the context of games. At the moment, in most of this research there is no active BCI control by users. There is, for example, measuring and analysing of brain activity of persons engaged in the same task. There is the general aim of researching how this engagement shows in their brain activity. One can also aim to learn from this and maybe support and improve this joint activity. This can then be done off-line, taking care of better conditions for future joint activity, or even in real-time, i.e. when the joint activity takes place, and then using this information to guide the users in their activity.

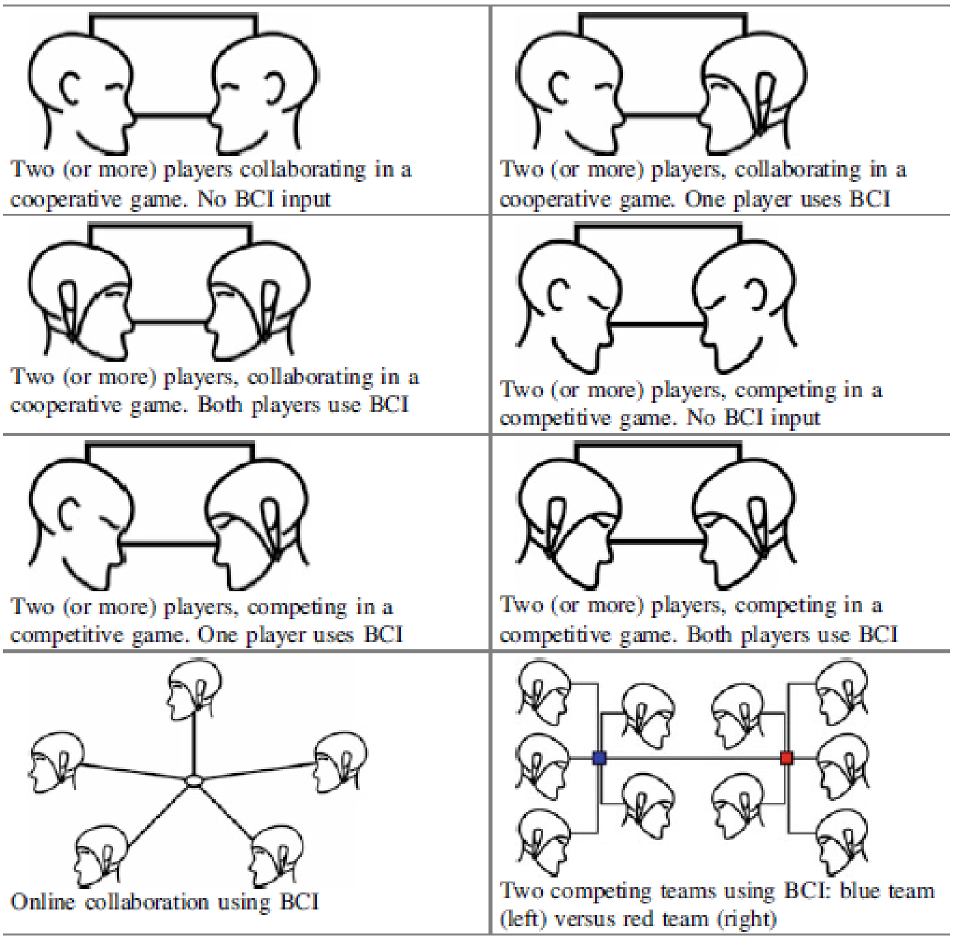


Figure 2.2: Various ways of competing and collaborating with and without BCI caps (from [46]).

Whenever there is joint activity, the assumption is that there is some synchrony visible in the brain activity of the participants. A conversation is obviously a joint activity and coordination and nonverbal synchrony, including mimicking, is a well-known phenomenon. Furthermore, as reported in [68], there is also a spatiotemporal coupling of the speaker's and the listener's brain activity. In this research fMRI was used to record brain activity, and the results support the idea that brain activity from different persons can be measured, analysed and integrated in order to be used as a source of information to guide behaviour and to control or adapt an environment in which the persons perform their activity. As is the case in other research on speaker-listener synchrony, the tighter the coupling between activities, the more successful is the joint task. As a possible application, one could model a social robot or an embodied agent such that its awareness of this synchrony can be used to have real-time adaptation of behaviour.

From this two-person activity, a multi-party or team activity can be generalized (see Figure 2.2). What kind of brain activity can we detect and integrate when we have a team of 'players' (not necessarily players in a game, but rather generally, persons involved in a joint activity)? Could we get information about progress (successful collaboration) and use this information to improve conditions for such team activity? And, as a next step, support and improve the joint activity based on real-time analysis and integration? During a meeting, for example, we could decide and make group members aware that there is a convergence or divergence of opinions. In a multi-user game with participating teams, such information (obtained in real-time) can certainly help to win the game. Undoubtedly, game, entertainment and artistic environments can be designed in such a way that each kind of combination of one and more persons, individual and joint voluntary control of brain activity and other, not consciously produced brain activity, can get a role in the environment.

2.3 Understanding cooperation

Cooperation is fundamental for well-functioning human societies. To better understand how cooperation both succeeds and fails, recent research in cognitive neuroscience has begun to explore novel paradigms to examine how cooperative mechanisms may be encoded in the brain. This approach attempts to discriminate and model the important processes in cooperative behaviour, by combining psychophysiological or neuroimaging techniques with simple tasks adapted from experimental economics [67].

2.3.1 Game theory

A good starting point for studies of social decision making is game theory [74]. In its original formulation, game theory attempts to find the strategies that a group of decision makers will converge on, as they try to maximize their own payoffs. One essential concept in game theory is the Nash equilibrium. Nash equilibrium refers to a set of strategies from which no individual players can increase their payoffs by changing their strategies unilaterally [44]. Stated simply, two players are in Nash equilibrium if Player A is making the best decision he can, taking into account Player B's decision while Player B's decision remains unchanged, and Player B is making the best decision he can, taking into account Player A's decision while Player A's decision remains unchanged.

As a first example we will use the two-player competitive game known as Chicken (see Figure 2.3a). In this game, two drivers are driving towards each other on a collision course: one must swerve, or both may die in the crash, but if one driver swerves and the other does not, the one who swerved will be called a "chicken", i.e. a coward. For the Chicken game with a symmetrical payoff matrix (as in Figure 2.3a), the two pure strategy Nash equilibria correspond to players choosing different options and a mixed strategy Nash equilibrium exists when players swerve 90% and move straight 10% of the time. Nevertheless, the predictions based on the Nash equilibrium are often systematically violated for such competitive games [10, 18].

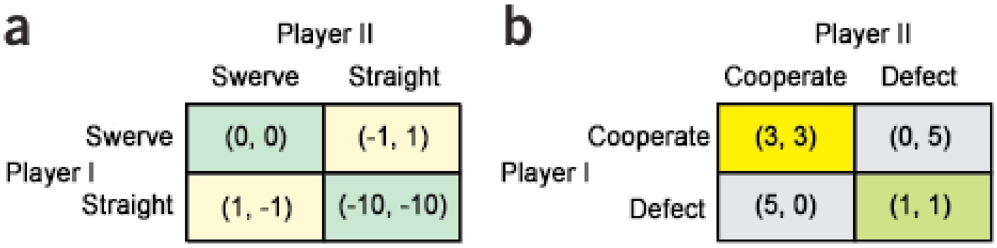


Figure 2.3: Payoff matrices for two game theory dilemmas. **(a)** The Chicken game. A pair of numbers within each pair of parentheses indicates the payoffs to players I and II, respectively. **(b)** The prisoner's dilemma game. A pair of numbers within the parentheses indicates the payoffs to players I and II, respectively. The yellow and green rectangles correspond to mutual cooperation and mutual defection, respectively, whereas the grey rectangles indicate unreciprocated cooperation (adapted from [37]).

How game theory can be used to investigate cooperation and altruism is illustrated by a well-studied game, the prisoner's dilemma [55]. The two players in this game can each choose between cooperation and defection (see Figure 2.3b). The largest payoff to the player occurs when he or she defects and their partner cooperates, with the worst outcome when the decisions are reversed. Mutual cooperation yields a modest payoff to both players, whereas mutual defection provides a lesser amount to each. If this game is played only once and the players care only about their own payoffs, both players should defect, which corresponds to the Nash equilibrium for this game. In reality and in laboratory experiments, however, these assumptions are frequently violated and players exhibit much more trust than expected, with mutual cooperation occurring about 50% of the time.

Games can also be played repeatedly, often among the same set of players. This makes it possible for some players to train others to deviate from the equilibrium predictions for one-shot games. In addition, humans often cooperate in prisoner's dilemma games, whether the game is one-shot or repeated [60]. Therefore, for humans, decision-making in social contexts may not be entirely driven by self-interest, but at least partially by preferences regarding the well-being of other individuals. In fact, cooperation and altruistic behaviours are abundant and a key factor in human societies [19].

2.3.2 Neural correlates of social decision-making

Pairing social-dilemma tasks like the Prisoner's Dilemma game with psychophysiological measures enables insight into human decision-making. Even though the current study examines event-related potential (ERP) correlates of cooperation and defection, functional magnetic resonance imaging (fMRI) studies are important to understand the brain regions associated with such processes.

The noninvasive nature of neuroimaging makes it possible to investigate the neural mechanisms of complex social decision-making in humans. On the other hand, the signals measured, such as blood oxygen level–dependent (BOLD) signals, merely reflect the activity of individual neurons in an indirect way. In particular, BOLD signals in fMRI experiments are suspected to reflect inputs to a given brain area more closely than outputs from it [40]. In imaging studies, many brain areas that are involved in reward evaluation and reinforcement learning, such as the striatum, insula and orbitofrontal cortex, are also recruited during social decision-making (see Figure 2.4).

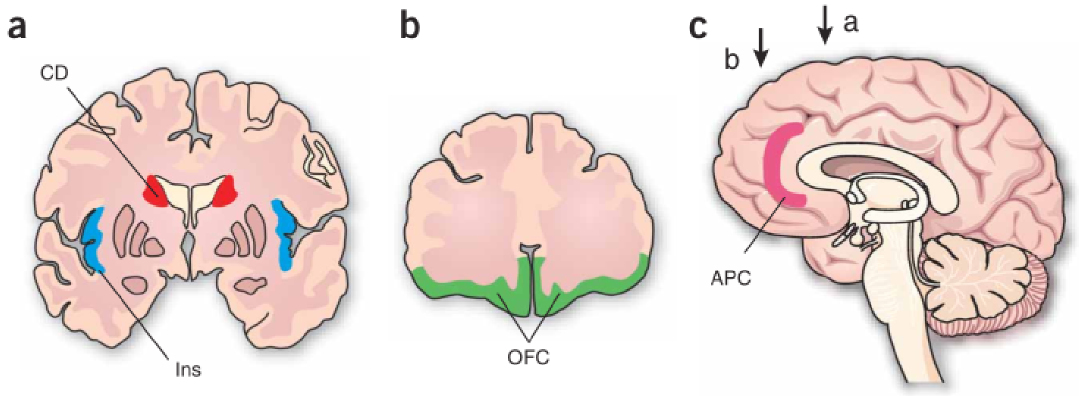


Figure 2.4: Brain areas involved in social decision-making **(a,b)** Coronal sections of the human brain showing the caudate nucleus (CD), the insula (Ins) and the orbitofrontal cortex (OFC). **(c)** Sagittal section showing the anterior paracingulate cortex (APC). Arrows indicate approximate locations of the sections shown in **a** and **b** (from [37]).

One of the areas that is critical in socially interactive decision-making is the striatum. For example, during the prisoner's dilemma game, cooperation results in a positive BOLD response in the ventral striatum when cooperation is reciprocated by the partner, but produces a negative BOLD response in the same areas when the cooperation is not reciprocated [56, 57]. In addition, the caudate nucleus appears to function in learning reward values of stimuli and tracking an opponent's decision to reciprocate or not reciprocate cooperation in the prisoner's dilemma game [56, 57].

Unreciprocated cooperation in particular is associated with activation of the insula. For example, during the ultimatum game, unfair offers produce stronger activation in the recipient's anterior insula when they are rejected than when they are accepted [63]. Because the insula is involved in evaluation of various negative emotional states, such as disgust [77], its activation suggests that it may mark negative social interactions in an effort to learn to avoid them in the future [58]. Comparing players' brain activity during the ultimatum game and the dictator game has also shown that the dorsolateral prefrontal cortex, lateral orbitofrontal cortex and caudate nucleus are important in evaluating the threat of potential punishment [66].

Furthermore, there is the possibility that brain responses might change depending on whether a particular social interaction is perceived as competition or cooperation. Indeed, during a board game in which the subjects are required to interact competitively or cooperatively, several brain areas are activated differently depending on the nature of the interaction [17]. For example, compared to competition, cooperation results in stronger activation in the anterior frontal cortex and medial orbitofrontal cortex.

Many neuroimaging studies find that social interactions with human players produce stronger activations than similar interactions with computer players in several brain areas [22], typically including the anterior paracingulate cortex (see Figure 2.4c), a region that might be important in representing mental states of others [21, 22].

So far, aside from neuroimaging, a few studies have used psychophysiological measures to better understand decision-making in social dilemma games [6, 54, 75]. This area of research is guided by the assumption that the feedback about another person's cheating or cooperation elicits ERPs from the same brain processes that monitor outcomes in other performance domains [62, 63]. Wang and colleagues [75] have postulated that two ERP components should be particularly sensitive to the valence and motivational relevance of outcomes in social dilemma games: the feedback-related negativity (FRN) and the feedback P300.

The feedback-related negativity is a negative deflection in the ERP at anterior and central electrode locations between 250 and 300 ms after feedback onset. It is believed to be generated in the anterior cingulate cortex (ACC) as a response to the conflict between a desired and an actual outcome [27]. Its amplitude is enhanced when participants fail to achieve a desired feedback [75, 78].

The second ERP component reflecting evaluations of feedback is the P300, a broadly distributed, positive deflection in the ERP between 300 and 600 ms after feedback onset with a maximum over medial central and medial posterior electrodes. Different brain structures are probably involved in its generation, including the ACC and the parietal cortex [39]. The P300 is often thought to reflect the amount of attentional resources devoted to information about rewards and losses [78]. This component can also be used to build brain-computer interfaces, and in particular BCI games [20].

The next chapter describes in further detail the recent neurophysiological research on social decision-making.

3

Related Work

This chapter explores the recent research conducted in social decision-making as well as physiological data gathering during gaming. Finally we present some examples of current multiplayer BCI games.

3.1 Neurophysiological studies on social decision-making

Decision-making is challenging because the outcomes from a particular action are rarely fully predictable. Furthermore, interactions among multiple decision makers in a social group show some additional features [37]. First, behaviours of humans and animals can change frequently, as they seek to maximize their self-interest according to the information available from their environment. Second, social interactions open the possibilities of competition and cooperation. In this section we look at neurophysiological studies on social decision-making from two perspectives: by analysing event-related potentials (ERPs) or brain oscillatory activity.

3.1.1 Event-related potentials

A constant aspect of decision-making is the need to adapt decision strategies based on recent outcomes. Cohen & Ranganath [12] tested the hypothesis that this flexibility emerges through a reinforcement learning process, in which reward prediction errors are used dynamically to adjust representations of decision options. Event-related brain potentials (ERPs) were recorded while subjects played a strategic economic game against a computer opponent to evaluate how neural responses to outcomes are related to subsequent decision-making. The analysis of ERP data focused on the feedback-related negativity (FRN), an outcome-locked potential thought to reflect a neural prediction error signal. This research found that the magnitude of ERPs after losing to the computer opponent predicted whether subjects would change decision behaviour on the subsequent trial, which was consistent with predictions of a computational reinforcement learning model.

In an attempt to examine human decision-making when the outcome is not entirely within one person's control, Wang et al. [75] used the Chicken Game to study the psychophysiological correlates of interpersonal cooperation and defection. In this social dilemma task, two players independently choose either to safely cooperate with, or riskily defect against, the other player. Choosing to defect allows maximal personal gains if the other player cooperates; however, if both players choose to defect each earn the worst outcome. The P300 was larger when participants chose to defect and when the other partner cooperated, suggesting that the monetary gains associated with an opponent's cooperation elicited more attention. To examine the feedback-related negativity at medial anterior electrodes, difference waves (dFRN) were created by subtracting the trials in which partners cooperated from trials in which partners defected. Results showed that the dFRN had a higher amplitude when participants chose to cooperate, rather than defect, possibly reflecting the participant's disappointment when the opponent did not reciprocate cooperation.

In order to examine the cognitive foundations of reciprocal exchange, Bell et al. [6] combined an iterated prisoner's dilemma game with psychophysiological measures. Participants played four rounds of the game with virtual partners who either cooperated or defected. In the control condition, only the partners' faces were shown but no interaction took place, and the round had no result. While playing, the partners' behaviours were consistent in the first three rounds of the game, but in the last round some of the partners unexpectedly changed strategies. In the first round of the game, the feedback about a partner's decision elicited a P300, which was more pronounced for cooperation and defecting in comparison to the control condition, but did not differ between conditions. In the last round, both the feedback-related negativity and the P300 were sensitive to expectancy violations. There was no consistent evidence for a negativity bias, that is, enhanced allocation of attention to feedback about another person defecting in comparison to cooperating.

The experience of current outcomes influences future decisions in various ways. The neural mechanism of this phenomenon may help to clarify the determinants of decision-making. Zhang et al. [79] focused on the relationship between cortical electrical signals following current outcome presentation and subsequent behavioural output in a risk decision-making scenario. The participants completed a risky gambling task by choosing between a high- and a low-risk option in each trial during EEG data collection.This study found that risk-taking strategies significantly modulated mean amplitudes of the ERP component P300, particularly at central regions of the scalp. The event-related spectral perturbation and the inter-trial coherence measurements of the independent component analysis (ICA) data indicated that the "stay" vs. "switch" electrophysiological difference associated with subsequent decision-making was mainly due to medial frontal theta and left/right mu independent components.

3.1.2 Brain oscillatory activity

EEG oscillations recorded both within and over the medial frontal cortex have been linked to a range of cognitive functions, including positive and negative feedback processing. Nevertheless, medial frontal oscillatory characteristics during decision-making remain largely unknown. Cohen et al. [13] examined oscillatory activity of the human medial frontal cortex recorded while subjects played a competitive decision-making game. Distinct patterns of power and cross-trial phase coherence in multiple frequency bands were observed during different decision-related processes, like feedback anticipation when compared to feedback processing. Decision and feedback processing were accompanied by a broadband increase in cross-trial phase coherence at around 220 ms, and dynamic fluctuations in power. Feedback anticipation was accompanied by a shift in the power spectrum from relatively lower (delta and theta) to higher (alpha and beta) power. Power and cross-trial phase coherence were greater following losses compared to wins in theta, alpha, and beta frequency bands, but were greater following wins compared to losses in the delta band. This study also found that oscillation power in alpha and beta frequency bands was synchronized with the phase of delta and theta oscillations (so called "phase–amplitude coupling"). This synchronization differed between losses and wins, suggesting that phase– amplitude coupling might reflect a mechanism of feedback valence coding in the medial frontal cortex.

In social interactions, the perception of how risky our decisions are depends on how we anticipate other people's behaviours. Billeke et al. [7] used EEG to study the perception of social risk, in subjects playing the role of proposers in an iterated ultimatum game in pairs. Based on the previous behaviours, both players' actions were classified as high-risk (HR) or low-risk (LR) offers. The HR offers have, by definition, higher rejection probability and higher variability of possible outcome than the LR offers. Rejections of LR offers elicited both a stronger medial frontal negativity and a higher prefrontal theta activity than rejections of HR offers. Another interesting find was that the trial-by-trial variation in alpha activity in the medial prefrontal, posterior temporal, and inferior parietal cortex was specifically modulated by risk and, together with theta activity in the prefrontal and posterior cingulate cortex, predicted the proposer's subsequent behaviour. These results were able to show that alpha and theta oscillations are sensitive to social risk and are involved in the regulation of social decisions.

3.2 Measuring activity during gaming

One useful way to gather insight into player experiences is by measuring human physiological activity. Physiological measures such as electrocardiography (ECG), electromyography (EMG), electroencephalography (EEG) and skin conductance have recently gained some attention in game research and interest is growing rapidly [32]. Physiological measurements provide a continuous, real-time, non-invasive, objective way to evaluate the game experience. The best results, however, require controlled experiments with careful monitoring of variables, large enough sample sizes and expertise in electrical signal processing.

Previous studies have attempted to capture game experience or to demonstrate the psychological effects of gaming using physiological data. Others have used real-time measures to adapt game features to the players' physiology. Various sorts of physiological indicators are also utilized when evaluating some game design choices.

We are particularly interested in EEG as it can be used simultaneously as a way to monitor player activity as well as used to control a game via BCI. EEG is able to provide data about the brain's electrical activity with millisecond accuracy. The signal can be examined for event-related potentials (ERP) evoked by specific events, or for changes in the power of different frequency bands evoked by specific game events or observed over longer periods (the entire game session).

Ninaus et al. [48] have reviewed the use of neurophysiological methods in serious games and virtual environments, including EEG as the most often used method in a gaming environment. For example, ERPs can be used to gather information on cognitive workload during gaming. In so called dual-task paradigms, infrequent game-unrelated stimuli such as audio cues are presented during playing games. These stimuli can elicit ERPs in the EEG. There is evidence that the amplitude of these ERPs varies depending on the cognitive workload induced by playing a game [3].

In addition to analysing time-locked ERPs, the EEG can be recorded continuously during a gaming session. The continuous EEG oscillations during gaming may then be compared with the EEG activity measured during a resting or baseline period, before or after playing a game. These EEG oscillations can shed light on cognitive and emotional processes underlying the gaming process [45]. For example, Salminen & Ravaja [61] examined oscillatory brain responses evoked by video game events, and reported that gaming events with different cognitive demands were associated with different changes in EEG oscillations, with some reflecting increased cortical activation and arousal while others reflected a relaxed state.

Using a non-invasive EEG set, Bakaoukas et al. [5] have also examined brain activity while subjects played three different computer games in both a noisy and a quiet environment. Results were obtained from analysing the rhythmic activity of the brain between a range of 2–45 Hz, focusing on the Alpha and Beta rhythm waves. Signal analysis confirmed the existence of differences in the brain activity during engagement with different categories of games. However, there is still a number of other influential factors, such as the interaction procedure, the overall game-play, the surrounding environment, and the presence of opponents.

Another interesting route is to use neurophysiological methods to examine game related subjective experiences. Plotnikov et al. [53] have reported initial data on the monitoring of the player flow status with a commercial 4 electrode EEG. The study examined if it is possible to statistically distinguish between conditions of flow and boredom. The initial results are promising and enable further research. Stevens et al. [69] have also studied team cognition using BCI, using wireless EEG headsets to measure attention, engagement and mental workload of the members of a team that has to play a serious game.

To this date, the use of EEG in game research has not been very abundant, possibly due to the complicated nature of the signal, which combined with a complex stimulus produces a variety of methodological challenges.

3.3 Multiplayer BCI games

In this section we describe the most relevant multiplayer BCI games recently developed in the community.

- **Brainball**

One of the earliest examples of a competitive BCI game is Brainball [26], a two-player game where both EEGs are measured and a relaxation score is derived from the ratio between the alpha and beta activity in the EEG signal. The relaxation score is used to move a steel ball across the table away from the most relaxed player; when the ball is almost at the opponent's side, and players realize they are winning, they tend to get excited and lose.

- **BrainArena**

Similar to Brainball, BrainArena [9] is a simple football game with a ball and goalposts displayed on a screen in front of the two players. There exist two versions of the game, a collaborative and a competitive one. The players wear EEG caps and use motor imagery (imaging left or right hand movement) to get the ball rolling in the direction of the goalposts. In the competitive version their actions are opposed and the player with the best performance wins, in the collaborative version the brain activities are merged and players steer the ball in the desired direction. Thus, in the competitive version it can be seen as a motor imagery version of the BrainBall game.

Figure 3.1: Two users playing BrainArena in a competitive trial (from [41]).

- **BCI in World of Warcraft**

An extremely popular multiplayer game currently on the market is World of Warcraft™, a massively multiplayer online roleplaying game (MMORPG) developed by Blizzard Entertainment®, Inc. In this game, the user may choose to play an elf druid who can shape-shift into animal forms. In bear form, for example, the druid is better protected against physical attacks by the thick skin, and is also a stronger attacker with sharp claws and teeth. In their normal elf form, they are much more fragile, but can cast effective spells for damage to knock out enemies from a distance as well as to heal oneself. This game was used as a platform for two prototypes [71], serving to show how BCI could be applied as an additional modality in a standard application currently on the market.

In AlphaWoW, this shape-shifting is controlled by the user's parietal alpha activity, with conventional mouse and keyboard input still being used for the other game controls. According to Cantero et al. [11], high alpha measured at the parietal lobe is related to a relaxed alertness. The opposite of this relaxed state would be some kind of sense of stress or agitation, which would have a natural relation to the more aggressive bear form.

IntuiWoW was developed to examine how different mental tasks have on the user experience. Three different mental task pairs were compared: (1) stressing to bear versus relaxing to elf form, similar to AlphaWoW, (2) mentally reciting a spell (a different text for each of the two shapes), and (3) feeling like a bear or elf, depending on what you want to change into. Results seemed to indicate that in this particular situation the users based their preference for mental tasks mainly on how well they were recognized by the system.

- **Mind the Sheep!**

To explore the influence of adding BCI input on collaboration in a multiplayer game, Mind the Sheep! was developed [49], a BCI game where the player needs to herd a flock of sheep across a field by commanding a group of herding dogs (Figure 2.5). The aim is to fence in all the sheep as quickly as possible. The game can be played by a single player as well as by two players collaboratively.

Figure 3.2: Screenshot from Mind the Sheep! (from [23]).

Both a BCI and non-BCI version of the game were developed. In the BCI version, dogs are highlighted in constant speed so as to evoke an SSVEP or P300 response. This game could be used to investigate the social interaction between the players in BCI and non-BCI situations. There are however challenges associated with this study: BCI acquisition methods, such as the EEG in this game, are intolerant to noise caused by movements or speech. Another interesting direction would be to find out how different modalities and BCI paradigms (SSVEP and P300) affect user experience.

4

Methodology

Since the present work is part of a larger research project, designed to also study the effects of emotion elicitation in a BCI game [14], and in order to meet the goals established in section 1.2, we will split this work into two separate steps:

- *Cooperative multiplayer BCI game*: The first step is to design and build a functional BCI game that serves both research intents. This game should encourage cooperative behaviours between players as well as present conditions to elicit different emotions. We opt for developing a collaborative multiplayer BCI system with two players that requires cooperative decisions during game play. As we intend the gaming experience to be close to that of a commercial grade game, proper game design guidelines will be followed.

- *Iterated two-person social dilemmas*: The second step is to design and implement a non-BCI game inspired by game theory social dilemmas that fits the purpose of this research and allows us to compare results with recent state-of-the-art findings of decision-making research. We opt to develop a game comprised of iterated dilemmas where two players are required to make cooperative or competitive decisions, while their brain activity is recorded using EEG. This controlled setting functions to reduce artefacts from movements and talking that would be generated during a typical BCI game session.

We believe that splitting the work in these two steps will help us reach the previously established goals. The multiplayer BCI game will be used to study the dynamics occurring between players during cooperative game play. With that intent, we will study not only the players' overall experience with the game, such as measures of engagement and competence, but also the social dynamics between players, such as feelings of empathy and behavioural involvement while playing. The interaction paradigm's accuracy and fitness to the overall game design will also be evaluated. The game theory social dilemmas, on the other hand, will serve to explore the decision-making neural correlates that can be extracted from a time-locked EEG signal in a controlled setting and the feasibility of using these measures while playing a cooperative game. The social dynamics between players as well as the strategies used while playing will also be evaluated for this game. We intend to categorise brain activity corresponding to cooperative game decisions in a controlled setting such as the two-person social dilemmas in order to test the suitability of using this activity to extend a cooperative BCI game, either actively (to control the game) or passively (to simply amplify the experience).

5

Game Design

In this chapter we define the design requirements and describe the methods and tools used to develop the game *Kessel Run*. We also describe the development of the game theory *Dilemmas* application as well as how all the software was integrated.

5.1 Cooperative game design requirements

When designing games, BCI or not, it is important to establish the general guidelines that should be followed in order to guarantee a fun experience for the players. With this in mind, we derive a set of requirements from good design theories applied in BCI games, mostly from the theories of Flow [15] and Paradox of Control [59]. The Flow theory defines immersion in a game as a state in which the player is actively engaged and where his skills match the challenge level of the game. The Paradox of Control, on the other hand, assumes that in a state of Flow the player must feel in control of the events, while at the same time sensing the possibility of losing control due to his own failure. Put together, these theories basically state that in order to achieve Flow the player has to feel both in control of his skills and challenged by the game.

Based on the Flow components noted by Csikszentmihalyi [15] and summarized by van Veen [72], we formulated a set of requirements that must be implemented in order to achieve proper game design:

- The game must feature a clear goal.
- The game must have clear rules.
- The game must challenge the players' skills.
- The game should be controlled by the BCI paradigm.

In addition, it is also necessary to take into consideration the fact that *Kessel Run* must be a cooperative multiplayer game. Several attempts have been made to identify the building blocks and the essential components of collaborative games. Wendel et al. have combined and augmented previous guidelines with the purpose to stimulate the development of social skills such as team-work, communication, and coordination during game play [76]. Some of the most important components that can be used in the design of cooperative games are a common goal/success, collaborative tasks, inter-dependent roles among players and communication.

Based on the components identified by Wendel et al. [76], we add the list of requirements to achieve the desired interaction between players in a cooperative game:

- The players must have a common success.
- The game must feature collaborative tasks.
- The players should have inter-dependent roles.
- The game should allow for communication between the players.

5.2 The game *Kessel Run*

Inspired by the lore of the Star Wars™ films, the game *Kessel Run* was developed using the personal license of the Unity 5[1] game engine. The game consists of a main menu (see Figure 5.1) and a virtual game environment set in an asteroid field in space (see Figure 5.2). The User Interface (UI) graphics were designed to transmit all the information the players might need during the play time in a simple and straightforward way. Game assets such as 3D models, graphic sprites and sounds were downloaded from the Unity Asset Store [1] and OpenGameArt.org [2] media repositories.

Figure 5.1: Screenshot of *Kessel Run*'s main menu.

5.2.1 The goal

Kessel Run is a space race game where two players work together to navigate a spaceship through a field of asteroids. The goal of the game is to last the longest amount of time (up to 2 minutes) in the asteroid field without losing all the fuel in the spaceship. If players last the full 2 minutes of the race, the amount of fuel left in the spaceship is taken as their game score.

[1]Unity 5, © 2017 Unity Technologies - *https://unity3d.com*

5.2.2 Game elements

The starting main menu (see Figure 5.1) consisted of two drop-down choice buttons, one for difficulty level (easy or hard) and the other for affective adaptation (on or off, not used in this study). After choosing the game options, the button "GO!" starts the game scene, presenting a confirmation window that reminds the experimenter to verify if all systems are properly connected. To facilitate this task, two colored circles were added to the game UI, one for each BCI system. The circles are orange when the BCI system is not connected and turn green when the system is successfully connected. After making sure the hardware is set up correctly and the players are ready to start, the experimenter can press the button "Start Game" and the game run will begin.

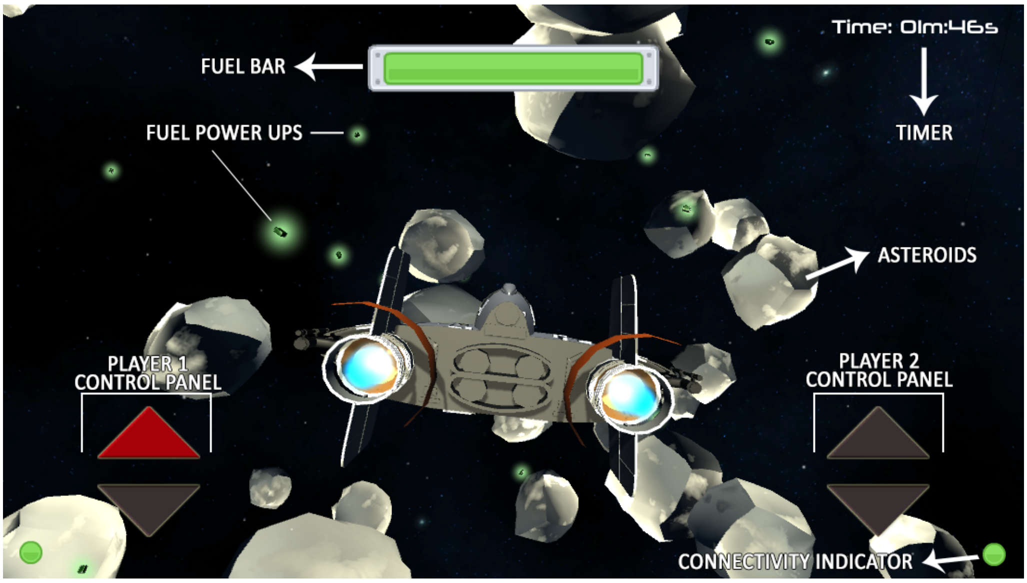


Figure 5.2: Screenshot of *Kessel Run*'s game scene showing the UI and game elements.

In the game scene (see Figure 5.2) several elements can be found:

- **Spaceship**

  Object controlled by the players. The spaceship is always moving forward and has two engines, side by side, each controlled by one player. A player can only control one side engine, except in the special situation of 'Take Over'. When one player "takes over", he/she controls both engines and the spaceship can only move up or down in the game space.

- **Timer**

  Element of the UI that counts down the time left until the end of the run. The timer starts counting down from 2 minutes and the run ends when the time is up or when players are out of fuel. In the last 30 seconds the text turns from white to red to remind the players the race is almost over.

- **Fuel bar**

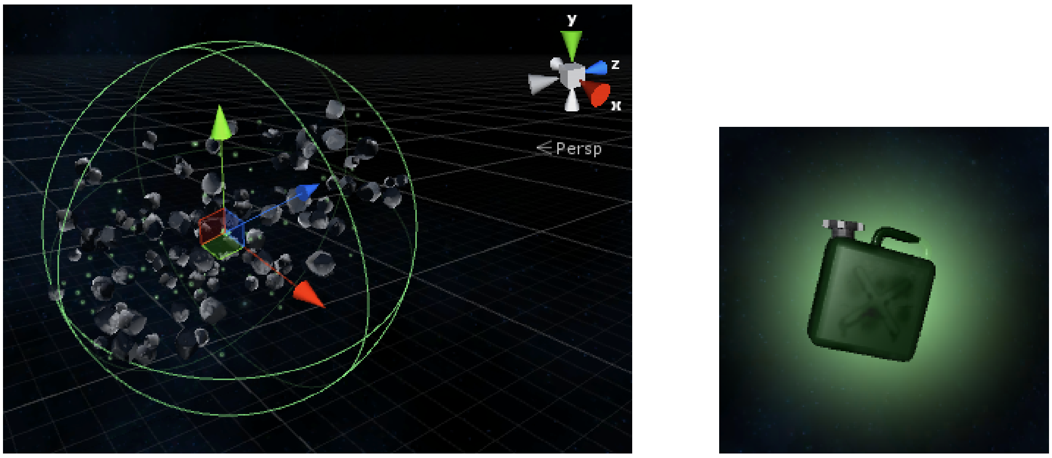
  Element of the UI representing the shared health of the players. The fuel of the spaceship serves as the players' in-game "health" for each game run. The race lasts for 2 minutes or until the fuel is completely lost. If the run lasts the full 2 minutes, the amount of fuel left in the spaceship is recorded as the game's score. The fuel does not go down with time but is only reduced in case of collision with an asteroid.

- **Asteroids**

  Obstacles present in the game space that players should avoid colliding with. Colliding with asteroids makes the spaceship lose 5% of its initial fuel. Asteroids are procedurally generated around the spaceship with random initial size and rotation (see Figure 5.3a).

- **Fuel cans**

  Power up objects scattered around the game space that refill the spaceship fuel (see Figure 5.3b). Every fuel can gathered by the players recovers 5% of the fuel lost. In case the fuel bar is already full, gathering fuel cans has no effect.



(a) (b)

Figure 5.3: *Kessel Run* game graphics: **(a)** procedural generation of asteroids in a sphere around the spaceship, **(b)** fuel can with a green glowing effect.

- **Control panel**

  Element of the UI that indicates in which direction each engine of the spaceship (i.e. player) is moving. Two pairs of up-down arrow indicators, one for each player, are located on the left and right corners of the game interface. The colour of the arrows turns from grey to red when the spaceship is moving in that direction. For example, in Figure 5.2, only the left engine is moving up, and the rest of the arrows are accordingly grey.

- **Take Over button**

  Floating virtual button that gives full control of the spaceship to one of the players. The 'Take Over' button shows up in the UI for 5 seconds intervals every 20 seconds. The player who first presses a physical button when the 'Take Over' button is showing gains total control of the ship for 10 seconds. While a player is "taking over" the virtual button changes form to indicate the fact (see Figure 5.4). After this time the spaceship is again controlled by both players. This mechanic was added to increase the gameplay choices, since players can take use the 'Take Over' as a competitive approach to controlling the game.

(a)

(b)

Figure 5.4: *Kessel Run*'s interface graphics for 'Take Over': **(a)** virtual button before any player "takes over", **(b)** virtual button sprite pressed down and glowing to indicate when one player is "taking over".

5.2.3 Rules

The gameplay consists of players cooperatively piloting the spaceship, avoiding colliding with asteroids and gathering enough fuel cans to last a 2-minute race. If the fuel bar reaches 0% at any given time, the game is over and the players lose. On contrary, if players accomplish to keep fuel above 0% until the 2-minute timer ends, the race is won. In case of a win, the fuel left is the final score of that game run. This allows players to choose their own goal, whether it be to simply beat the game or improve their final score.

Even though the whole game can be controlled via BCI, the players are also provided with one physical USB button (that sends a single key-press to the computer when pushed) they can push when they wish to 'Take Over'.

Two levels of difficulty were designed for the game *Kessel Run* in order to elicit different spectra of emotions (not analysed in this work) [14]. The easy mode is intended to be a challenging, yet relaxing experience for both players. The amount of asteroids in the game space is lower and there are more fuel cans available to pick up. The hard mode, on the other hand, was designed to be extremely challenging, with more asteroids scattered around and less fuel cans to gather. This harder level is expected to induce stress in the players and even a sense of frustration when failing to beat the game. Instead of losing 5% of fuel for every asteroid collision, the spaceship now loses 10% of its initial fuel and the game controls are randomly missed on purpose. To make it less evident for the players, every 2 seconds there is a 50% chance of becoming unresponsive for a random time between 0.5 and 2 seconds. Along with the difficulty tweaks, each mode also has different soundtracks: while the easy mode presents a calm electronic music, in hard mode the music is more upbeat to reflect the increase in difficulty.

5.2.4 Multiplayer controls

In a BCI game the control paradigm used determines a lot of the characteristics in the gameplay. Different paradigms will provide a distinct sense of control, speed of interaction, degrees of freedom and even the possibility to play socially. The first step was to choose which BCI paradigm was to be used in the game.

We opted to use the steady-state visually-evoked potentials (SSVEP) paradigm due to a number of reasons. First, it has the possibility of high information transfer rate even with a short training phase, having low requirements from the subject (89% of users are able to get 80% accuracy or higher after only a short training [73]). Second, it is relatively robust in respect to noise and artefacts, because the signal has to be averaged out during a short time. A downside is the flickering visual stimuli may cause some fatigue or tiredness if subjects use it for a long time. Because of this we decided to make each race last no more than 2 minutes and allow the players to rest in-between game runs.

In order to implement the SSVEP paradigm as a game controller we used two solid red LED panels placed on the top and bottom midline of each player's screen, to select two possible commands. The use of external LEDs as visual stimuli avoids the limited number of frequencies that can be used due to monitors' refresh rates. The light flickering is done at 15 and 12 Hz, detected on the 10-20 EEG system's Pz and/or Oz electrodes.

For the SSVEP classification we opted for the Canonical Correlation Analysis (CCA) method [8, 38]. The CCA algorithm is implemented in MATLAB® and runs in real-time during the game session. The algorithm uses blocks of 80 samples for each iteration on acquired data. Since the sampling frequency for our system is 512 Hz, a player's decision is made every 0.15 seconds, allowing a very smooth control. Before each game session, each player's algorithm settings are empirically defined by selecting a combination of electrodes Pz and/or Oz and a CCA threshold that offers the better performance.

The control mechanics of *Kessel Run* were carefully designed taking into account the BCI control paradigm used. Each player will have, attached to the top and bottom of the monitor they are playing the game, two LED panels. This way each player is presented with three possible choices (look at the top panel, the bottom one or not look at any LED panel). These three choices could possibly translate to three commands in game: each player can either move up, down or not move at all. With this in mind we designed the spaceship controls to allow for a more fluid motion even though each player can only move in two directions. The solution was to attribute the up/down controls to two engines in the spaceship. (see Figure 5.5).

When a single player is looking up, for example, only his side of the spaceship moves up, causing a rotating motion of the spaceship. If this is the player controlling the left engine, the spaceship rotates in a clockwise manner, and correspondingly counter-clockwise in case of the right engine player moving up. A single player looking down has the opposite effect. However, when both players are simultaneously moving up, the entire spaceship moves upwards, and respectively downwards if both players choose to move down at the same time. In case of the players moving in separate directions the spaceship will rotate even faster, in a clockwise manner if the left engine is moving up and the right is moving down, or counter-clockwise on the contrary.

The in-game freedom of movement was designed to make players cooperate in order to more easily dodge asteroids and gather fuel cans, decreasing the challenge when players work together and ultimately allowing them to win the game. Nevertheless, players have inter-dependent roles and should communicate in order to avoid making mistakes that can lead to losing the game. The only exception is when players are in 'Take Over' mode. When a player is "taking over" control of

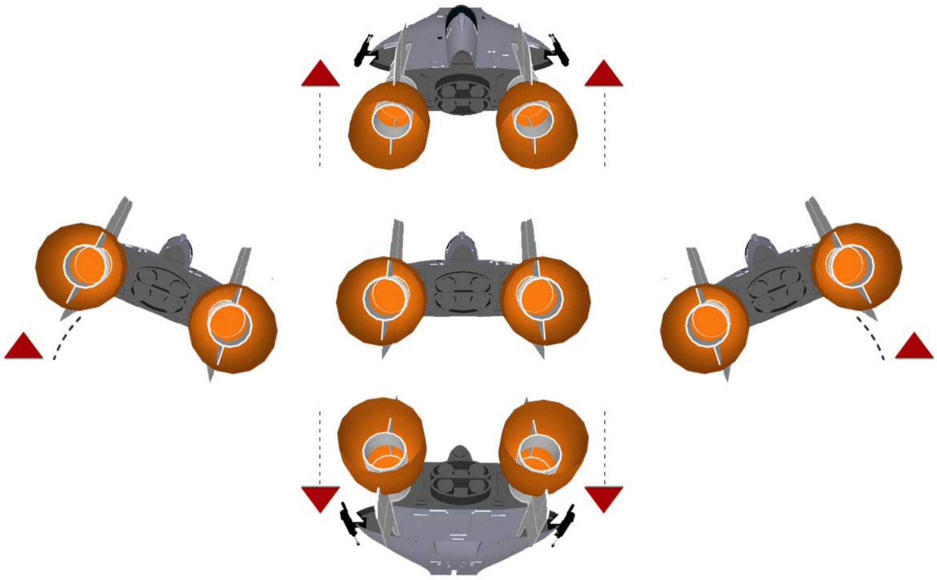


Figure 5.5: Illustration of *Kessel Run*'s multiplayer control mechanics. Each player controls the direction (up/down) of one engine. If both players move their engines up (or down), the ship moves in that direction. Otherwise, the spaceship rotates in the selected direction (e.g. left engine rotates clockwise when the player controlling it moves up).

the spaceship, he/she overrides both engines and is capable of moving the spaceship fully upwards or downwards only by looking at his/her own LED panels. This essentially means that in the short period of 'Take Over' a single player takes the role of two perfectly synchronised players, allowing for a much easier navigation in the game environment.

5.3 The game *Dilemmas*

Five games based on some of the most famous and well-studied game theory dilemmas were designed in Unity 5 in order to study cooperative and defective decisions made by the players in a controlled, time-locked setting, after having played the full session of *Kessel Run*.

5.3.1 The goal

In contrast with the cooperative game *Kessel Run*, in *Dilemmas* players no longer have a mutual win condition. This does not mean the game cannot be played collaboratively, but each player is awarded his/her personal score. The players can then choose to play the game in two ways: either maximize their personal score to defeat the adversary or maximize the group scores by making decisions that benefit both players equally.

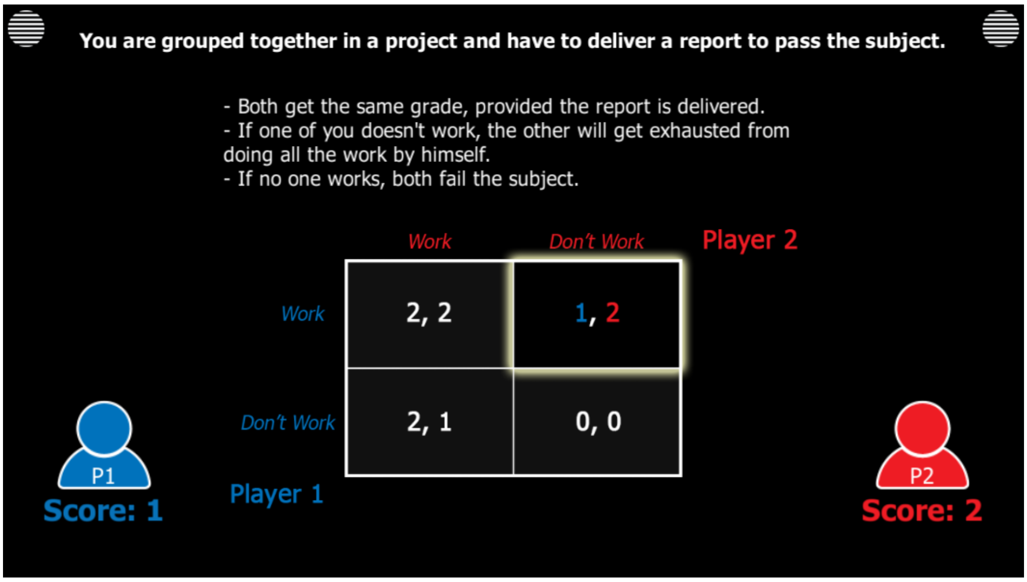


Figure 5.6: Screenshot of the game *Dilemmas* after the first round of the "group project" dilemma. Players are colour-coded (blue and red) and can see their current score under their player icon. After both players made their decision the application highlights the outcome and the respective points are assigned to each player. Top corner graphics represent good system connection.

5.3.2 Rules

In each of these five games, the players are presented with a situation where each one must make a choice between two options, resulting in one of four possible outcomes. Each outcome has different consequences for each player, represented by the score attributed to that player (see Figure 5.6).

Each game consists of five rounds played sequentially, resulting in a total of 25 (5×5) trials. In each round, players see the game description and the payoff matrix outlining the possible outcomes for each combination of decisions made by them. When both players have made their decision, the round outcome is shown for 4 seconds and points are attributed to each player. Since the same game is played again sequentially, players can adapt their strategies based on the previous result. After the five rounds, the final score for that game is presented and the player with the most points is considered that game's winner (both win in a tie). There was a 10 second interval in-between different games.

The game descriptions for the five different games played during *Dilemmas* are described below, each with their respective payoff matrix.

- **Group project** (see Table 5.1)

  You are grouped together in a project and have to deliver a report to pass the subject.

  - *Both get the same grade, provided the report is delivered.*
  - *If one of you doesn't work, the other will get exhausted from doing all the work by himself.*
  - *If no one works, both fail the subject.*

		Player 2	
		Work	*Don't work*
Player 1	*Work*	(2, 2)	(1, 2)
	Don't work	(2, 1)	(0, 0)

Table 5.1: Payoff matrix for the game “Group project”. The pure strategy Nash equilibria are *(Work, Work)*, *(Work, Don’t work)* and *(Don’t work, Work)*. In this game, “working” is cooperation and “not working” is defection.

- **Chicken game (or Hawk-Dove)** (see Table 5.2)

  You are in a confrontation with each other, and can either fight or stand down.

  - *If both choose to stand down, all problems are settled and everyone goes their own way.*
  - *If only one chooses to fight, he/she will show dominance and the other will just leave with some bruises.*
  - *If both decide to start fighting, everyone will get severely hurt.*

		Player 2	
		Attack	*Stand down*
Player 1	*Attack*	(0, 0)	(3, 1)
	Stand down	(1, 3)	(2, 2)

Table 5.2: Payoff matrix for the “Chicken” game. The pure strategy Nash equilibria are *(Attack, Stand down)* and *(Stand down, Attack)*. There also exists a Nash equilibrium in mixed strategies, when both Player 1 and Player 2 choose *Attack/Stand down* with 0.5 probability they each have an expected payout of 1.5. In this game, “standing down” is cooperation and “attacking” is defection.

- **Closed briefcase (Prisoner’s dilemma)** (see Table 5.3)

  You have to do a closed briefcase exchange with each other. You value the good they have higher than the one you have, but either of you can choose to bring an empty briefcase.

  - *If both deliver their goods, everyone gets what they wanted.*
  - *If one decides to keep their goods and the other delivers their own, he/she will get both and the other person will have nothing.*
  - *If both keep their goods, everyone will keep what they previously had and will not have any new goods.*

- **Share or steal** (see Table 5.4)

  You are both in a game show and both are given the choice to share or steal the money you earned.

  - *If both decide to share the money, each one gets half the amount.*
  - *If only one chooses to steal, that player will keep all the money to himself.*

		Player 2	
		Deliver	*Keep*
Player 1	*Deliver*	$(2,2)$	$(0,3)$
	Keep	$(3,0)$	$(1,1)$

Table 5.3: Payoff matrix for the game "Closed briefcase". The unique pure strategy Nash equilibria is *(Keep, Keep)*. In this game, "delivering" is cooperation and "keeping" is defection.

		Player 2	
		Share	*Steal*
Player 1	*Share*	$(1,1)$	$(0,2)$
	Steal	$(2,0)$	$(0,0)$

Table 5.4: Payoff matrix for the game "Share or steal". The pure strategy Nash equilibria are *(Share, Steal)*, *(Steal, Share)* and *(Steal, Steal)*. In this game, "sharing" is cooperation and "stealing" is defection.

  - *If both choose to steal the money, no one gets anything.*

- **Stag hunt** (see Table 5.5)

  You are hunting for food with each other, and can either hunt for a stag (an adult male deer) *or a rabbit. A stag provides much more meat but requires both hunters' efforts or it will escape.*

  - *If both aim for the stag, you get to share a huge amount of meat.*
  - *If one chooses to go for the rabbit, he/she will catch it but the other will get nothing.*
  - *If both aim for the rabbit, you share the meat.*

		Player 2	
		Stag	*Rabbit*
Player 1	*Stag*	$(3,3)$	$(0,2)$
	Rabbit	$(2,0)$	$(1,1)$

Table 5.5: Payoff matrix for the game "Stag hunt". The pure strategy Nash equilibria are *(Stag, Stag)* and *(Rabbit, Rabbit)*. There also exists a Nash equilibrium in mixed strategies, when both Player 1 and Player 2 choose *Stag/Rabbit* with 0.5 probability they each have an expected payout of 1.5. In this game, choosing "stag" is cooperation and "rabbit" is defection.

A decision to cooperate does not imply a harmful effect to the other player, but a decision to defect implies a negative effect is caused to the other player (lower score). For every game, a player wins a round when he/she earns more points than the adversary or both earn the same amount of maximum points they can earn together.

The game order is randomized for each experimental session. Subjects wear the BioSemi ActiveTwo EEG caps during the full duration of *Dilemmas* but make their decisions with the keyboard. During game-play, all decision key-presses and outcome presentations (i.e. stimulus onset) are saved as triggers in the recording.

5.4 Software integration

From the previous sections we have established the two software products that are part of the system used in this experiment: the Unity game engine to design both the *Kessel Run* and *Dilemmas* games, and MATLAB® to run the SSVEP classification algorithm in real-time when playing *Kessel Run*.

We have used Unity as the core game development tool for its ease-of-use and focus on portability. It is a cross-platform game engine that can be used to develop video games for all the major platforms: PC, consoles, mobile devices and websites. Unity's drag-and-drop editor allows for easy and quick manipulation of all the components in the game project. Object behaviours can be programmed using common scripting languages such as JavaScript and C#, giving the developers greater flexibility to use the language they are most familiar with.

MATLAB® is the tool we use to process EEG signals and run the SSVEP classification algorithm. MATLAB is a numerical computing environment often used in data processing due to its powerful MATLAB scripting language. It allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and is capable of interfacing with programs written in other languages.

In order to integrate these two pieces of software and handle the EEG data acquisition, we decided to use the versatile BCI2000 platform [2]. BCI2000 is a software suite for brain-computer interface research, commonly used for data acquisition, stimulus presentation, and brain monitoring applications. Its versatility comes with supporting a variety of data acquisition systems, brain signals, and paradigms, as well as the ability to interact with other software such as MATLAB.

We use BCI2000 as the overall system manager during the experimental procedure. It is the nuclear software that handles the data acquisition and processing, signal communication to and from Unity (i.e. translating CCA results into player decisions and saving markers in the data), and general integration of all parts of the system.

Generally speaking, all BCI systems need the same four elements: data collection, signal processing, an output device and manual (or automatic) parametrisation and configuration. The BCI2000 suite is comprised of four modules that are responsible for these four different parts of the process, respectively: *Source*, *Signal Processing*, *Application*, and *Operator* (see Figure 5.7). The *Operator* module is responsible for the configuration interface, allowing the investigator to start and end the recording, adjust acquisition parameters and set preferences such as the saving directory, subject codes and event markers. The other three modules are specialized depending on the data acquiring system, the processing required and the end-user application.

In this experiment we have used two different configurations, for the *Kessel Run* and the *Dilemmas* games. During *Kessel Run* we are gathering data and processing

[2]BCI2000® from Schalk Lab - *http://bci2000.org*

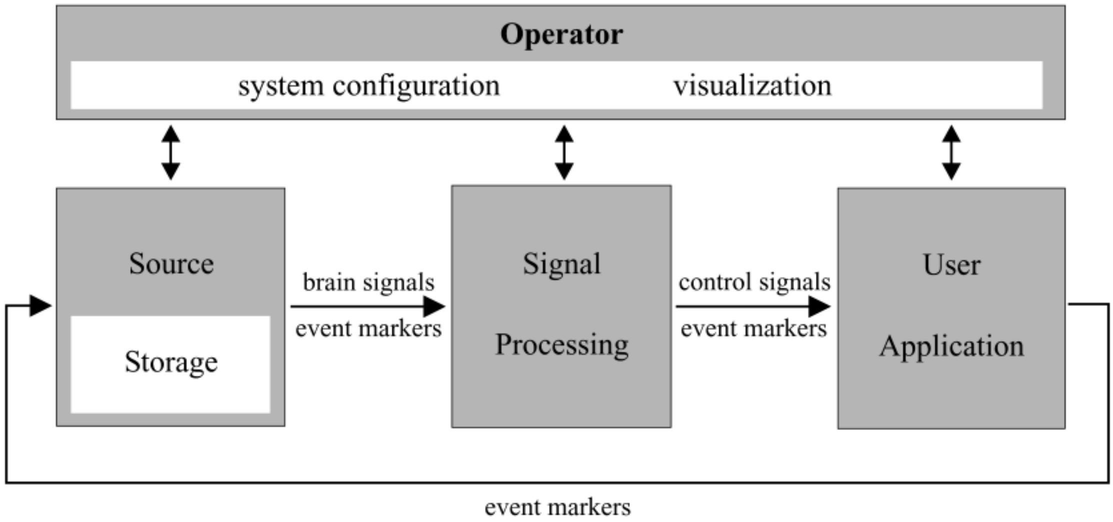


Figure 5.7: BCI2000 design and its four modules: *Operator*, *Source*, *Signal Processing*, and *Application*. The Operator module acts as a central relay for system configuration and online presentation of results to the investigator. During operation, information (i.e., signals, parameters, or event markers) is communicated from Source to Signal Processing to User Application and back to Source (from [64])

it on real-time for the SSVEP BCI control of the game. In contrast to the first stage, during the *Dilemmas* part of the experiment, we are simply interested in gathering EEG data that will be later processed and analysed.

For the part of the experiment were subjects played *Kessel Run* the following modules were selected:

- *Source* module: `FieldTripBufferSource` (from the Fieldtrip[3] toolbox by Oostenveld et al. [50]) for data acquisition from the BioSemi ActiveTwo[4] system. In this stage of the experiment this module was chosen over the standard `Biosemi2` since Fieldtrip supports the acquisition of other peripheral sensors from BioSemi, such as galvanic skin response (not used in this work), instead of EEG signals only.

- *Signal Processing* module: `MatlabFilter` to process the data with a MATLAB function (`*.m` file) that computes the CCA classification and returns the output to the BCI2000 pipeline.

- *Application* module: `DummyApplication`, meaning no output application was chosen since the game is simply running on the *Kessel Run* application built on Unity.

Meanwhile, for the *Dilemmas* part of the experiment the following modules were selected:

- *Source* module: `Biosemi2` for data acquisition from the BioSemi ActiveTwo system.

[3]FieldTrip toolbox for EEG/MEG-analysis, from Donders Institute for Brain, Cognition and Behaviour - *http://http://www.fieldtriptoolbox.org/*

[4]BioSemi B.V. - *https://biosemi.com/*

- *Signal Processing* module: `DummySignalProcessing` because in this stage of the experiment we are simply gathering data, so no processing is required.

- *Application* module: `DummyApplication`, since no output application is needed as the game is simply running on the *Dilemmas* application built on Unity.

The BCI2000 modular design makes it an exceedingly flexible platform. Any changes to the processing algorithm can be quickly implemented by editing the MATLAB code. The whole system can also be implemented on a different BCI device simply by changing the *Source* module. In fact, we have successfully tested the *Kessel Run* game using an Emotiv EPOC[5] headset, even though the signal quality is far inferior to the BioSemi ActiveTwo system.

An important limitation to take into account is that a single BCI2000 session only acquires signals from one BCI system at a time. This implies that for multiplayer games like *Kessel Run* where two BioSemi systems are used, we need at least two computers. We opted for a set-up of three computers, with two destined to acquire, process and send signals from the two BCI systems to a third computer that is running the Unity applications (see Figure 5.8).

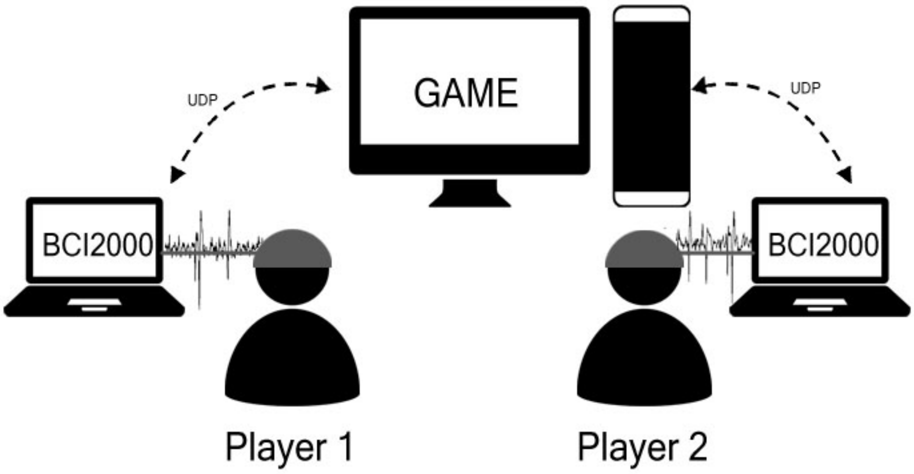


Figure 5.8: Software communication set-up. One computer per subject processes the incoming EEG data, converts it to game actions and sends the signals to the dedicated computer running the game via UDP. The game returns marker signals to be stored in the data.

5.4.1 Communication protocol

Even though BCI2000 does not have a module for interfacing directly with Unity, it has a built-in feature that uses the *User Datagram Protocol* (UDP) and enables communication with external applications. The `AppConnector` provides a bi-directional link to exchange information with external processes running on the same machine, or on a different machine over a local network.

UDP is a connection-less protocol suitable for applications that need fast, efficient transmission, such as games. However, there is no guarantee that the messages or

[5]Emotiv EPOC, ©Emotiv Inc. - *https://www.emotiv.com/*

packets sent keep the same ordering or reach the destination at all. To keep the probability of losses as low as possible, and their consequences as local as possible, messages used in `AppConnector` have been designed to be short, self-contained, and redundantly encoded in a human readable fashion [64].

To enable message communication with Unity it was necessary to open two IP ports, one sender and one receiver, and set the same ports in `AppConnector` to exchange BCI2000 messages. In our experiment, particularly in the game *Kessel Run*, UDP messages sent from BCI2000 refer to the SSVEP classification that translates to game actions. Meanwhile, for both *Kessel Run* and the *Dilemmas* game, messages sent from Unity to BCI2000 relate to game events and are saved as markers in the data: beginning and end of runs, player decisions and game scores.

6

Experiment

In this section we describe the experimental set-up and procedure adopted, as well as the methodology for analysing the data collected in this work.

6.1 Subjects

All subjects that volunteered to take part in this experiment were students in the University of Twente. Participants were asked to bring a friend, and if no friend was available they were teamed up with another participant (for the call for participants, see Appendix A). Participants were 12 subjects (5 female) aged 22 to 31 (mean age = 23.8) that participated in pairs for a total of 6 game sessions. Each participant had a normal, or corrected to normal eyesight. All participants reported daily computer usage but one third reported playing digital games (computer, console or mobile) less than once a month. Half of the participants had no earlier experience with BCI at all, while the other half had interacted with a BCI at least once. All subjects read and signed an Informed Consent Form (see Appendix B), verified and approved by the Ethics Committee of the University of Twente. No subjects suffered from any neurological, psychiatric or other relevant diseases inadvisable to the participation in the experiment.

6.2 Materials

The set-up consisted of three computers: two for the EEG data acquisition and one to run the games on. EEG signals were acquired using a Biosemi ActiveTwo system for each participant. Even though the SSVEP selection method used only signals acquired from two electrodes, Pz and Oz, a full cap of 32 active Ag-AgCl electrodes placed according to the 10-20 international system was used. All signals were digitized at a 512 Hz sampling rate.

The computer running the Unity games was connected to two identical LCD monitors (1920 x 1080 resolution, 60 Hz refresh rate), one for each participant. The monitors were placed approximately at a 50 cm distance and centred with subjects' line of sight. Two pairs of red LED lights (10 cm x 10 cm) were mounted on both monitors, on the top and bottom mid-lines of the screen, as in Figure 6.1. Two USB buttons were placed near each player's dominant hand, to activate the 'Take Over' function during *Kessel Run*.

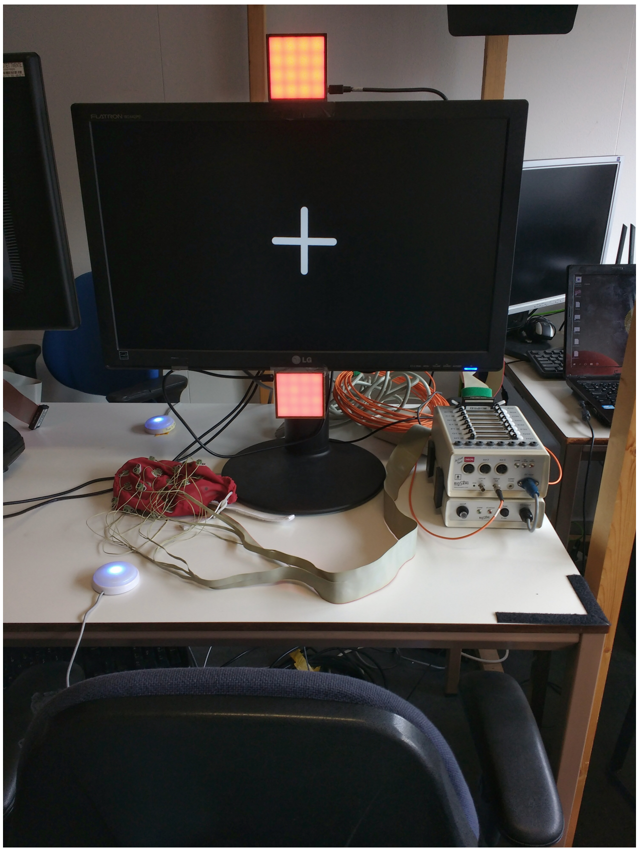


Figure 6.1: Screen set-up for the SSVEP training session.

Experiments were performed in a quiet, darkened laboratory. A table and two comfortable chairs were placed in the centre of the room so participants were facing each other. Each subject was looking as his/her own monitor and there was a gap between both monitors. While playing *Kessel Run*, participants could see each other as in Figure 6.2, which was meant to encourage them to communicate during game play. On the other hand, while playing *Dilemmas*, participants were not allowed to communicate and the gap was closed so they could not see each other any more.

6.3 Procedure

The full experimental protocol is described step-by-step in Appendix C. Before playing the games, every participant filled in a demographic questionnaire that also inquired about their gaming habits and previous BCI usage. After being explained the content of the experiment, the EEG caps and electrodes were placed on each participant. Good connectivity was ensured by applying electrolyte gel until all electrode offsets were lower than $\pm$ 20 mV. A short SSVEP training session of 80 seconds was recorded for off-line performance analysis and participant's CCA parameter definition (threshold and EGG channels used). In this session, participants were asked to look at the top and bottom LED lights, and at the fixation cross in the middle of the screen every 5 seconds, while their EEG data was acquired using the ActiView software from Biosemi.

Participants were given time to learn the game before playing *Kessel Run* for a total of eight runs. First they played four runs in easy mode, followed by four

Figure 6.2: Two participants playing *Kessel Run*.

runs in hard mode. At the end of each run, participants were asked to fill in a brief self-assessment questionnaire regarding their emotional experience in that particular run (not used in this work).

After playing the game *Kessel Run*, every participant filled questionnaires on Game Experience and Social Presence adapted from the Game Experience Questionnaire developed by IJsselsteijn et al. [28, 29, 34]. The first module assesses game experience as scores on six components: Challenge, Competence, Flow, Tension/Annoyance, Positive and Negative Affect. The social presence module investigates psychological and behavioural involvement of the player with other social entities, in this case the co-located person playing the game with them [34]. This module consists of three components: Behavioural Involvement, Psychological Involvement - Empathy and Psychological Involvement - Negative Feelings. An extra item was added to the social presence module to assess players' intentions to cooperate with one another: *'I felt inclined to work together with the other'*. For both questionnaires the items were presented on a scale of agreement from 0 to 4, in which 0 - 'not at all', 1 - 'slightly', 2 - 'moderately', 3 - 'fairly' and 4 - 'extremely'.

For the second part of the experiment subjects played the *Dilemmas* game. An example of a dilemma, different from the ones played, was presented to participants in order to explain the rules and how they would play the game. Keyboards were placed in front of each participant and they were told which keys to press to make decisions in the game. After playing the five runs of the five different dilemma games in random order, participants were asked to fill in the social presence module again, this time regarding their experience playing the *Dilemmas* game. Appendix D compiles all questionnaires used throughout the whole experiment (demographic, game experience and social presence).

By the end of the experiment, EEG head caps were removed and participants were given towels and shampoo to remove any electrolyte gel residues from their hair. The entire experiment took approximately 1 hour and 30 minutes from start to finish.

6.4 Result analysis methodology

All data analysis was performed under MATLAB® with the Fieldtrip toolbox [50]. Statistical computing was performed in R software.

The training session recorded early on in the experiment was used to evaluate individual participants' SSVEP performance. Subjects were recorded in three conditions: looking at a 12 Hz flickering light source (bottom LED panel), a 15 Hz light source (top panel) and at the centre of the screen (fixation cross). For each of these conditions, raw EEG signals from the electrodes Pz and Oz were cut into trials of 80 samples. No preprocessing was performed to minimize computing costs and time. Each trial was used in the CCA algorithm to determine its correlation with sine and cosine reference signals at 12 and 15 Hz. Empirical thresholds for correlation were determined upon visual inspection of CCA results of each condition for each reference signal. Each participant was attributed a threshold and a combination of electrodes (Oz and/or Pz) that resulted in the best classification.

During the *Kessel Run* game play, EEG signals are split into similar trials, and classified into game actions based on the maximum of CCA correlation. If the highest correlation (for each of the reference signals) is greater than the threshold for a particular participant, the corresponding frequency determines the decision. If the maximum correlation is with the 12 Hz signal, the player moves down, and moves up in case the maximum correlation is with the 15 Hz signal. Whenever the threshold is not met, no action is transmitted to the game and the player keeps staying in the centre.

For the study of game experience in *Kessel Run*, the scores for each item were grouped according to their respective user experience categories: Challenge, Competence, Flow, Tension/Annoyance, Positive and Negative Affect. For the social presence module, items were grouped in three components: Behavioural Involvement, Psychological Involvement - Empathy and Psychological Involvement - Negative Feelings. After grouping, mean and standard deviation were derived from participant scores for both modules. For the single item *'I felt inclined to work together with the other'* only the frequency of responses and mean score were determined. For the *Dilemmas* game, social presence was the only module analysed, with the same procedure.

The EEG data collected during the experimental session was processed and analysed using the Fieldtrip toolbox [50] for MATLAB®. The first pair of subjects was removed from this analysis due to experimental set-up differences. For both *Kessel Run* and *Dilemmas* recordings, individual subject data from the remaining 10 subjects was loaded and then re-referenced to common average and filtered with high-pass at 1 Hz and low-pass at 49 Hz Butterworth filters. No baseline correction or de-trending was performed at this point.

Continuous data was then segmented into trials of interest for several conditions with a custom Fieldtrip trial defining function. Any missing triggers in the EEG data were corrected with the data from their respective session partner. For trials defined based on a "key-press" trigger, the data was cut into [-2 1] second intervals for the following conditions:

- Takeover in *Kessel Run* per game difficulty (easy/hard) - variable number of trials per subject
- Decision (cooperate/defect) in the current trial of *Dilemmas* - 25 trials per subject

For trials defined based on a "result presentation" trigger (specific to the *Dilemmas* game), the data was cut into [-0.5 2] second intervals for the following conditions:

- Decision (cooperate/defect) in the current trial of *Dilemmas* - 25 trials per subject
- Decision (cooperate/defect) in the next trial of *Dilemmas* - 20 trials per subject
- Outcome (win/loss) in the current trial of *Dilemmas* - 25 trials per subject
- Outcome (win/loss) based on decision (cooperate/defect) in the current trial of *Dilemmas* - 25 trials per subject

Since the EEG data was recorded while subjects played interactive games, motion artefacts were present in the data. Noisy and/or faulty electrodes were visually identified and any channels with variance > 0.5 were repaired with the average of their neighbours. Even though it is not the most reliable method to repair bad channels close to each other, this served to reduce noise due to ocular and head movements when subjects were playing *Kessel Run* and looking at the LED lights, for example.

Trials were then categorized per condition and the time-locked average ERPs were computed for all conditions stated above. Grand average was performed across all subjects and results were plotted into topographic and time-locked signal plots for the electrode locations of interest: channels Fc1, Fc2, Fz and Cz. The Biosemi ActiveTwo 32-electrode layout was defined for 2D plotting.

Time-lock statistics (T-test performed with a Fieldtrip function) were calculated for the four outcome based on decision conditions in the game *Dilemmas*: cooperate-win, cooperate-lose, defect-win and defect-lose. Signal plot graphics highlighting the difference between conditions were drawn for the four channels of interest.

7

Results

In this section the results obtained from the experiment described in the previous section are presented. Findings for both the *Kessel Run* and *Dilemmas* games are briefly discussed.

7.1 The game *Kessel Run*

7.1.1 BCI Performance

Of the initial 12 participants, two (one pair) were excluded from this performance analysis due to changes in the experimental set-up. Results correspond to the training session that anticipated the game play of *Kessel Run*, in which players were told to look at a 12 Hz flickering light source, one at 15 Hz or look at a fixation cross in the centre of the screen.

	$\bar{X}(\sigma)$	Max	Min
Overall	55.3 (14.1)	78.9	34.1
12Hz	62.7 (12.6)	85.6	47.8
Centre	65.4 (20.8)	87.8	23.3
15Hz	37.8 (19.5)	80.0	20.0

Table 7.1: SSVEP performance descriptives from CCA classification (33.3% chance level).

The SSVEP-based BCI had, in general, lower than expected performance (see Table 7.1). Overall classification accuracy (i.e. the average accuracy among the 3 classes - choosing the 12 Hz or 15 Hz stimuli or choosing not to move by looking at the centre of the screen) was 55% on average, with a maximum of 79%. For the conditions of looking at the 12 Hz flickering LED and looking at the centre of the screen, performance was similar with average correct classification over 60%. The 15 Hz condition was the one with the lowest average accuracy (38%).

In Figure 7.1 the detailed results per participant are presented. Subject's performance for the 12 Hz condition (white bars) was consistently higher than for the 15 Hz condition (dark blue bars). The condition of looking at the fixation cross (light blue bars) had the best overall performance (65%) and the best maximum accuracy

(88%) of the three conditions. This means the system was best at detecting when subjects were not looking at a light source but at the game itself.

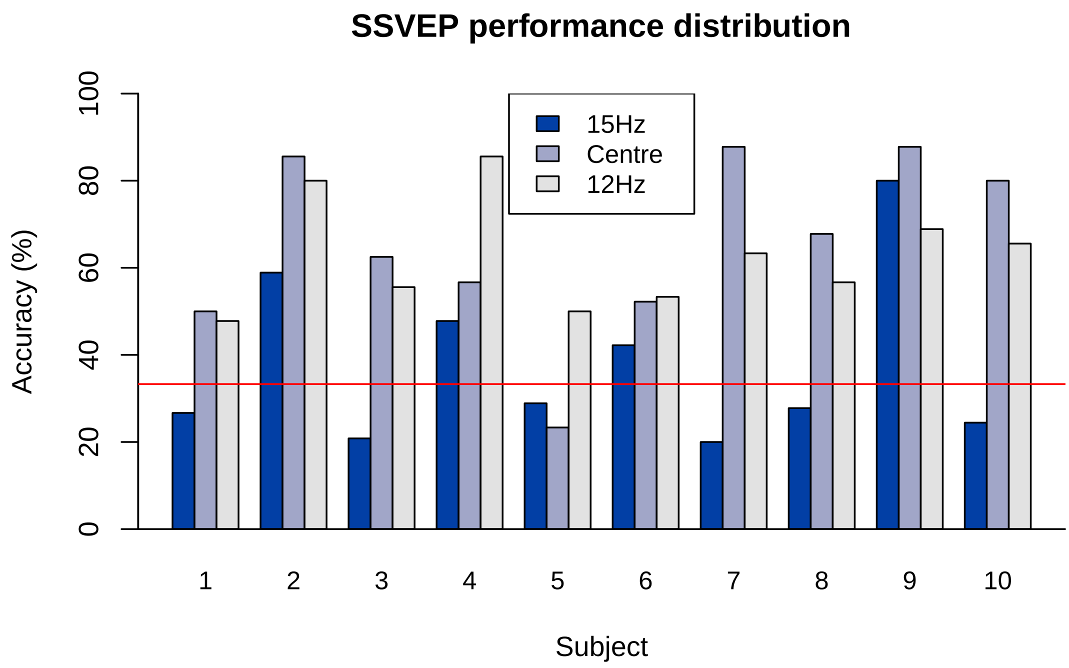


Figure 7.1: Distribution of SSVEP performance per subject during the training phase. In dark blue are the classification results when looking at the 15Hz flickering LED, in light blue the results when looking at the centre of the screen and in white the results when looking at the 12Hz flickering light.

The performance results for the 12 Hz stimuli were very close to the results for the centre condition. On the other hand, the accuracy for the 15 Hz stimuli was under the 33% chance level for most subjects ($median = 28\%$). The overall BCI performance decreased because participants could produce SSVEPs while focusing on the 12 Hz light source but the 15 Hz source was much harder to classify. These low accuracy results associated with the 15 Hz frequency are possibly related to the 12 Hz frequency being in the dominant alpha range. Considering the alpha range is increased during a relaxed mental state, it is possible that this deteriorated the CCA classification for the 15 Hz frequency.

Other authors have also found differences in CCA classification when using distinct frequencies. Hakvoort et al. [24] found that subject accuracy in a CCA-based detection method differs depending on frequencies used. Allison et al. [4] also found inter-subject differences regarding SSVEP robustness for certain combinations of frequencies.

A second factor influencing the overall BCI performance was the undesirable lighting in the laboratory. A good quality SSVEP requires the isolation of its visual stimuli from other light sources. Even though all experiments were performed in a darkened room, there still was ambient light present due to window gaps (visible in Figure 6.2). This escaping light reduced the relative brightness of the LEDs and caused the consequent loss in classification accuracy.

Furthermore, during the *Kessel Run* game play the BCI interaction was undoubtedly unlike the controlled training session. Players moved their heads rapidly to control the game and verbally communicated which caused signal noise and possibly disrupted the CCA classification. The performance is expected to be even lower because both the game and the BCI use the visual channel. Players have to decide to visually focus on the game itself or on a flickering light above or below the screen to issue the desired BCI command. The fast dynamics of the game lead to a rapid switching of focus which may give no time for the SSVEP to reach a steady state in the EEG signal.

Because the 15 Hz source was generally harder to classify, participants could hardly issue both commands to control the spaceship. Nevertheless, participants were able to adapt to the circumstances, placing their head in different positions or closer to the LED source for better SSVEP detection, or choosing to use only one of the controls (generally the 12 Hz). Another strategy was to use the 'Take Over' mechanic to their advantage.

Table 7.2: 'Take Over' mechanic descriptives per game difficulty in *Kessel Run*.

Difficulty	Total Takeovers	Takeovers per run	Average run time
Easy	25	1.042	118 s
Hard	17	0.708	56 s

Statistics for the use of the 'Take Over' mechanic during the game *Kessel Run* are presented in Table 7.2. Players "took over" more frequently in the Easy game mode than in Hard mode, but in Hard mode the runs were generally much shorter. Overall, 'takeovers' were used more frequently (considering average number per run and average run time) during the Hard difficulty, likely because the game was more challenging to beat (and control) and players were more familiar with the mechanic since the Hard mode runs followed four Easy mode runs.

When playing the game most players with good SSVEP performance decided to be the "captain" and control the spaceship themselves, while the player with the worst performance was in charge of indicating directions. This resulted in the "captain" using the 'Take Over' mechanic more often as it decreased the difficulty in controlling the spaceship. In Figure 7.2 the number of takeovers performed by each player is associated to their overall SSVEP performance.

There was the general tendency to "take over" more the better performance a subject had, observed by the trend line in Figure 7.2 and Pearson's correlation = 0.765. Players grasped how well they could control the game and communicated to establish a cooperative relation where the player with the better BCI performance would be responsible for control and the other focused on the game and was responsible for the direction commands.

Player adaptation to the low BCI performance in these different ways might result in a higher feel of control than what is foreseen based on their classification performance alone (determined solely by the training session), and reduce its impact on the user experience.

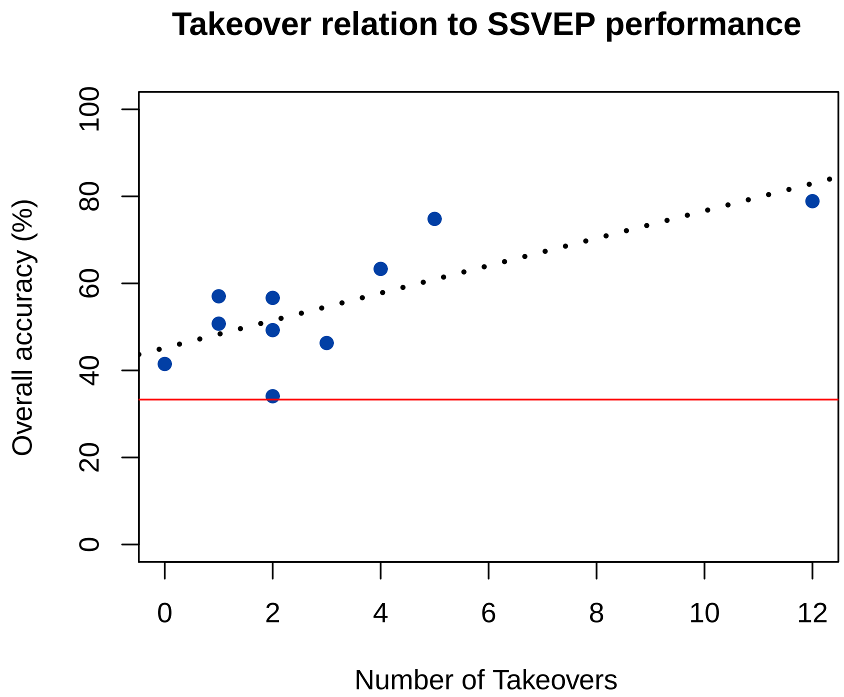


Figure 7.2: Scatter plot of number of Takeovers by each subject related to their personal overall SSVEP performance. Data was fitted with a linear regression (black dotted line) with equation $y = 3.15x + 45.19$, $R^2 = 0.534$. The horizontal red line represents the 33.3% chance level for SSVEP classification.

7.1.2 Game experience

To evaluate *Kessel Run*'s user experience as a digital game we grouped responses from the Game Experience questionnaire (GEQ) into key components and results are summarized in Figure 7.3. Detailed results for each component are presented in Appendix E.

Most likely due to low BCI performances, participants only felt slightly competent ($\overline{competence} = 1.1$) when playing the game. Interestingly enough, we observed that participants were able to adapt while playing *Kessel Run* even when not in full control of the BCI, as mentioned in the previous section. Teams often opted to move the spaceship in only one of their controllable directions in order to play together. Otherwise, when one player had a better BCI performance, he/she would be elected "captain" and take command of the ship while the other would indicate directions for where to move next. These strategies helped create a greater bond between players and lead to a predominantly positive affect during the game ($\overline{pos.affect} = 2.5$; $\overline{neg.affect} = 0.8$). Moreover, they also lead to a greater feel of immersion ($\overline{Flow} = 2.6$) during the game and a moderate to fair sense of challenge ($\overline{challenge} = 2.3$). When considering the questionnaire scores we can conclude that *Kessel Run* is an overall enjoyable game, specially when taking into account the participant's Flow scores, suggesting a good deployment of the good design requirements set in section 5.1.

There is certainly room for improvement in *Kessel Run*'s enjoyment and the

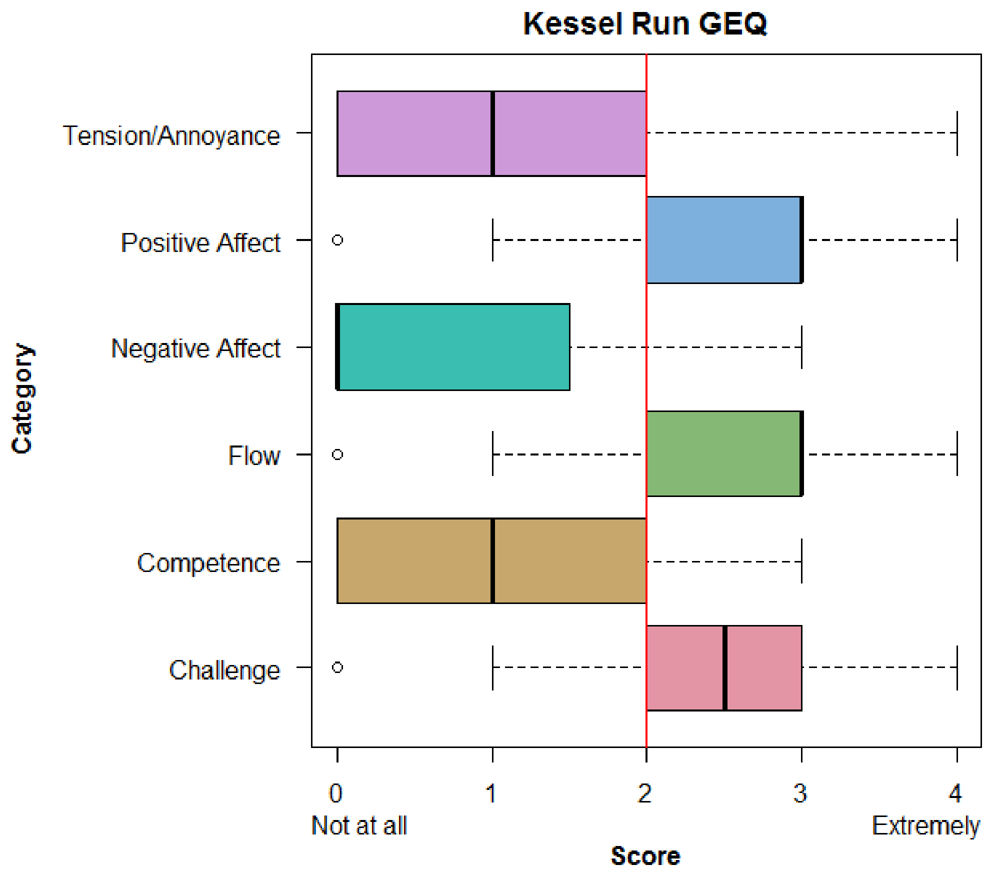


Figure 7.3: Box plots for the Game Experience questionnaire results, aggregated by component: Challenge, Competence, Flow, Tension/Annoyance, Positive and Negative Affect.

BCI paradigm selection seems to play an important role in the game's playability due to the low Competence scores observed. The choice of interaction paradigm plays a critical role in the playability of any BCI game. Influencing factors go well beyond the system accuracy: game characteristics such as pacing, controls and mechanics should all be taken into account when choosing the appropriate paradigm. We adopted the SSVEP paradigm to control *Kessel Run* due to its ease of implementation, fast classification, and intuitiveness while playing (players should look at the direction they want to go). However, this implied that whenever a player wanted to make a decision, he/she was required to shift focus away from the game and into the LED panels above and below the monitor, breaking the immersion and possibly interfering with the user experience. Another downside is the fact that exposure to flickering lights may strain the eyes after some minutes, depending on the subject. There would be benefits of switching the interaction paradigm to another based on induced activations (motor imagery or lateralized readiness potentials) instead of evoked responses as is the case of SSVEP, which could turn the overall experience more intuitive and fun.

7.1.3 Social experience

In order to evaluate the social experience of the subjects playing *Kessel Run* the responses to the Social Presence questionnaire (SPQ) were aggregated by component and results are summarized in Figure 7.4. Detailed results for each component are presented in Appendix F.

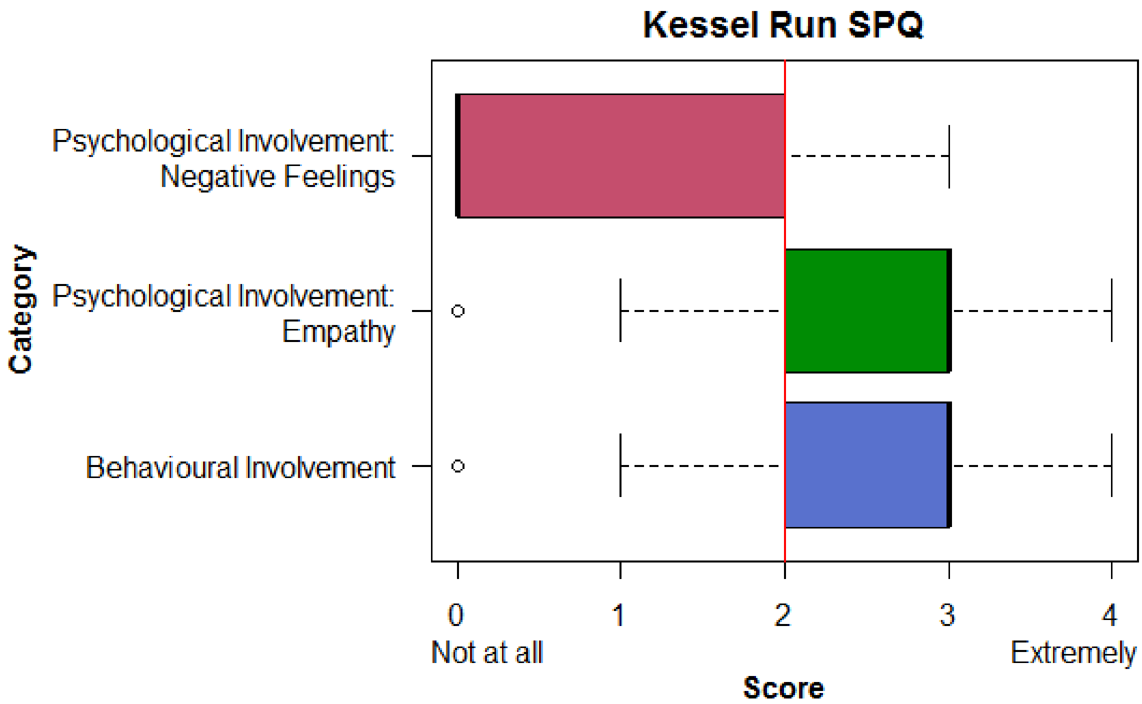


Figure 7.4: Boxplot for the answers on the Social Presence questionnaire for the game *Kessel Run*, for each of the three components: Behavioural Involvement, Psychological Involvement - Empathy and Psychological Involvement - Negative Feelings.

For the Behavioural Involvement component, all items had positive scores (mean above 2). This component included six items with mean scores ranging from 2.4 to 3.1 ($\overline{b.involvement} = 2.7$). This component measures the degree to which players feel their actions to be dependent on their co-players actions. Results suggest that players considered their actions fairly dependent on the other's actions', e.g. mean(*'What the other did affected what I did'*) = 2.8.

In the Psychological Involvement - Empathy component, all but one items had a mean score over 2 ($\overline{empathy} = 2.3$). Of all the six items included in this component, *'I admired the other'* was the only one with a negative mean score (mean = 1.0 'slightly'). This may be due to the fact that players only felt slightly competent playing the game and did not feel their co-players to be much more competent controlling the BCI. The remaining five items had mean scores ranging from 2.3 to 2.8. Players empathized with each other: mean(*'I empathized with the other'*) = 2.6 and found it fairly enjoyable to be with the other: mean(*'I found it enjoyable to be with the other'*) = 2.8.

For the Psychological Involvement - Negative Feelings component, the overall mean score was negative (mean under 2). Players only slightly indicated negative feelings towards the other ($\overline{neg.feelings} = 0.9$). This component included five items with mean scores ranging from 0.3 to 1.6. Players did not feel jealousy: mean(*'I felt* *jealous about the other'*) = 0.3 or revengeful towards the other player at all: mean(*'I felt revengeful'*) = 0.4. On the other hand, players felt moderately influenced by the other's moods: mean(*'I was influenced by the other's moods'*) = 1.6.

Figure 7.5: Frequency bar plot of answers to the item *'I felt inclined to work together with the other'* for the game *Kessel Run*.

The question *'I felt inclined to work together with the other'* was added to the questionnaire as a measure of intention to cooperate among the players. Results show that the majority of players (8 out of 12) gave the item a score of 3 or 4, agreeing 'fairly' or 'extremely' with the sentence (see Figure 7.5). The mean score for this item was 2.9, which means that overall, players felt 'fairly' inclined to work together with the other player. These results suggest that *Kessel Run* met the requirements proposed in section 5.1 for good cooperative game design.

As a social experience we can say that *Kessel Run* had a positive impact on players. The low SSVEP performance scores might have influenced the overall social presence. In one way, players with lower BCI accuracy may have felt more dependent on the other's actions, but this fact may have made players empathize more with each other. The frustration of players who could not reliably control the game may have influenced the mood of the co-player but overall the game did not elicit negative feelings towards the other player.

7.1.4 EEG potentials prior to button-press

EEG potentials recorded prior to the use of the 'Take Over' mechanic while playing *Kessel Run* were analysed for the two different game difficulties (Easy and Hard), to explore any correlations to game mode. This data was also compared to the potentials anticipating a button-press in the game *Dilemmas* (not considering game difficulty) in an attempt to match similar situations in both games. Four participants (two pairs) were excluded from this EEG analysis due to changes in experimental set-up and corrupted recordings. The EEG channels of interest (Fc1, Fc2, Fz and Cz) are located in the medial frontal region, relevant to the decision-making process.

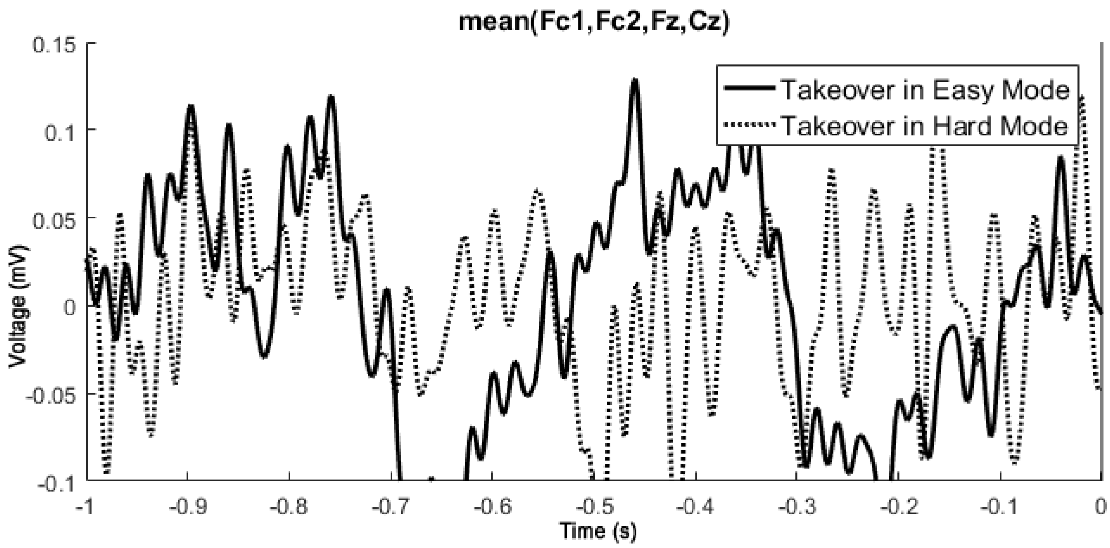


Figure 7.6: Average potential over the four medial frontal channels 1 second before players used the 'Take Over' mechanic in the Easy (full line) and Hard (dotted line) difficulties of *Kessel Run*.

In Figure 7.6 the average EEG potentials recorded 1 second prior to a 'Take Over' button-press are represented by game difficulty. Because not all subjects used the 'Take Over' mechanic, the only data available was from 13 trials recorded from 7 subjects in Easy mode and 13 trials from 8 subjects in Hard mode. Signals are noisy due to players' movements during the game and because the number of trials is very limited so there does not seem to be any present ERPs consistent with a decision to press the button in order to take control of the spaceship.

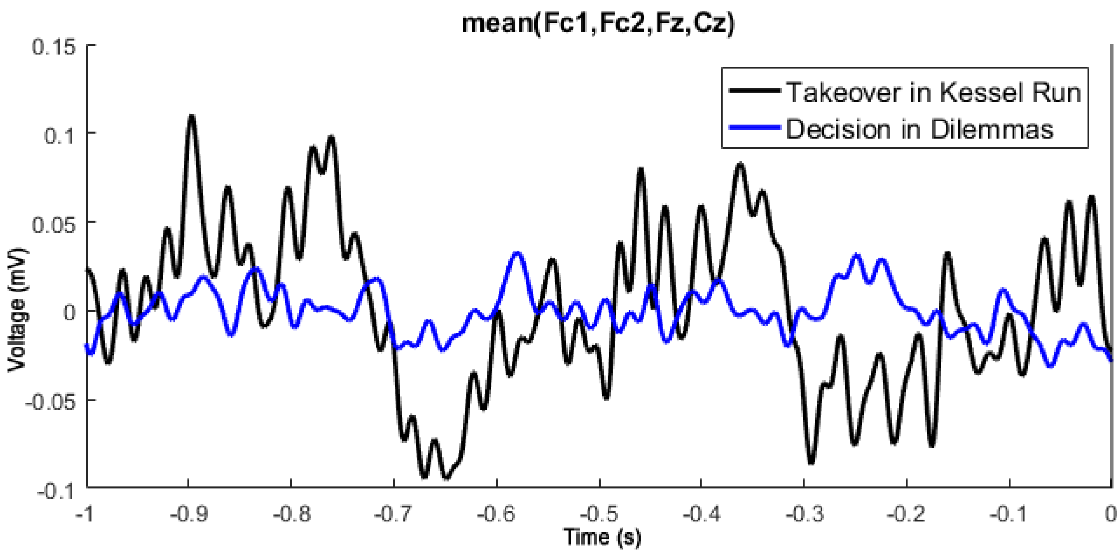


Figure 7.7: Average potential over the four medial frontal channels 1 second before players used the 'Take Over' mechanic in *Kessel Run* (black line) and before players pressed a key to make a decision (either cooperative or defective) in the game *Dilemmas* (blue line).

In Figure 7.7 the average EEG potentials recorded 1 second prior to a 'Take

Over' in *Kessel Run*, aggregated for both game difficulties, are represented against potentials recorded 1 second prior to a decision key-press in *Dilemmas*, aggregated for cooperative or defective decisions. The same 26 trials from 'Take Over' in *Kessel Run* were used but in *Dilemmas* each subject had to make a total of 25 decisions. The recordings of three subjects were excluded from this analysis and for another two subjects only 15 trials were extracted due to missing markers in the data file. The total of 205 decision trials from *Dilemmas* resulted in a much less noisy signal than the trials from 'Take Over' due to averaging.

In general, *Kessel Run* recordings are too noisy to extract any information on potentials anticipating decision-making. Because the 'Take Over' data is limited to a player's choice there are not too many trials and the grand average among subjects still contains large fluctuations.

Results seem to show no correlation between the two recordings for both games, which would be expected since the games are very distinct and the subject behaviours are not comparable. During *Kessel Run*, players were encouraged to talk with each other, and had to move their heads to look at the light sources and control the game. Furthermore, 'Take Over' was designed as a side mechanic in a game that does not require button-presses in the core gameplay, while in the game *Dilemmas* the key-presses are the only means of interaction with the game, and required to advance the game play.

It would be interesting to analyse the data for lateralized readiness potentials anticipating the decision making and consequent movement, but any future experiment should involve a much larger number of trials to gather a significant statistical result.

7.2 The game *Dilemmas*

7.2.1 Strategies and outcomes

The information on how the participants played the game *Dilemmas* was the first result analysed. Every game consisted of 5 trials, in a total of 25 trials recorded for every subject. For each trial, both the participant's decision (strategy) as well as the resulting outcome were recorded, depending on the strategy used by the co-participant. Table 7.3 presents the game statistics for the different strategies and outcomes in *Dilemmas*.

Table 7.3: Outcomes based on strategies used in *Dilemmas*.

	Won	Lost
Cooperated	178 *(59.3%)*	42*(14.0%)*
Defected	42 *(14.0%)*	38 *(12.7%)*

The majority of game decisions were cooperative (73.3%), while the defective decisions only amounted for 26.7% of the total plays. Because all the games are symmetrical, the number of trials where one subject defected and then won and where one subject cooperated and then lost are equal.

Game strategies were grouped by game type, for each of the five different game theory dilemmas included in the game *Dilemmas* (described in Section 5.3). Table

7.4 presents the strategy distribution for each game type.

Table 7.4: Strategies used in *Dilemmas* per game type.

Game type	Cooperation	Defection
Group Project	56	4
Chicken	44	16
Closed Briefcase	41	19
Split Steal	41	19
Stag Hunt	38	22
TOTAL	220	80

The cooperative strategy was exceptionally high for the Group Project game type with only 7% of defections, maybe because most participants were students and could relate to the situation presented in the dilemma. In fact, previous research has found that group identity can influence rates of cooperation even in the absence of communication [33]. For all the remaining game types, the defection rates lie between 26% and 36%.

Another interesting statistic is the fact that in 50% of the cases at least one player chose to defect in the last trial of a dilemma. This is a well-known phenomenon in repeated social dilemma games, as there is no risk of retaliation in the last round of the game [6]. Therefore, selfish individuals who in the first rounds cooperated merely out of fear of retaliation will switch to an uncooperative strategy [31]. Hence, cheating in the last round of a repeated social dilemma game may be indicative of a player's character. One possible solution to avoid last round defection is to randomize the number of rounds played in each social dilemma.

7.2.2 Social experience

For the game *Dilemmas* only the social experience of the subjects was evaluated. The summary of the Social Presence questionnaire (SPQ) results aggregated by component is shown in Figure 7.8. Detailed results for each component are presented in Appendix G.

For the Behavioural Involvement component, all items had positive scores (mean above 2). This component included six items with mean scores ranging from 2.7 to 3.3 ($\overline{b.involvement} = 3.0$), and it measures the degree to which players feel their actions to be dependent on their co-players actions. As expected due to the nature of this game, involvement was rather high. Players paid close attention to each other, mean(*'I paid close attention to the other'* = 3.1), as in every trial each subject is guessing what their opponent's next move might be. Players also considered their actions fairly dependent on the co-player's actions, mean(*'My actions depended on the other's actions'* = 3.3), and felt that their actions influenced the other's actions, mean(*'What I did affected what the other did'*) = 3.1.

In the Psychological Involvement - Empathy component, all but one items had a mean score over 2 ($\overline{empathy} = 2.4$). Of all the six items included in this component, *'I admired the other'* was the only one with a negative mean score (mean = 1.6). The remaining five items had mean scores ranging from 2.3 to 2.8. Opposite to a purely cooperative game like *Kessel Run*, *Dilemmas* can be seen by some players as purely

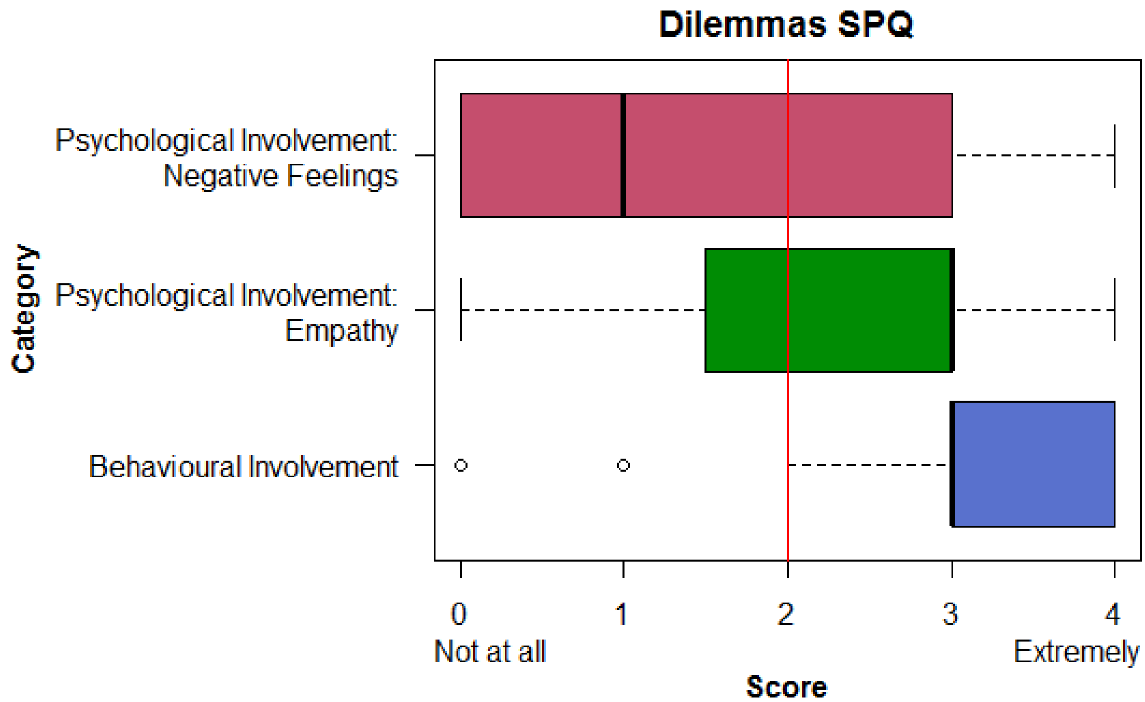


Figure 7.8: Boxplot for the answers on the Social Presence questionnaire for the Game Theory dilemmas, for each of the three components: Behavioural Involvement, Psychological Involvement - Empathy and Psychological Involvement - Negative Feelings.

competitive, which may reduce the feelings of empathy for the other player. Because of this, players only moderately empathized with the other, mean('I empathized with the other') = 2.3, but felt fairly connected, mean(*'I felt connected to the other'*) = 2.8, and found it enjoyable to be with the other, mean(*'I found it enjoyable to be with the other'*) = 2.8.

For the Psychological Involvement - Negative Feelings component, the overall mean score was negative (mean under 2). Players only indicated some negative feelings towards the other ($neg.feelings = 1.5$). This component included five items with mean scores ranging from 0.5 to 2.6. Players did not feel jealousy towards the other player, mean(*'I felt jealous about the other'*) = 0.5 but admitted to feeling some malicious delight during the game, mean(*'I felt schadenfreude (malicious delight)'*) = 1.5. Players felt their actions had an influence in the mood of the other, mean(*'I influenced the mood of the other'*) = 2.6, more than the contrary, mean(*'I was influenced by the other's moods'*) = 2.0. The immediate feedback on winning or losing after each trial may have influenced the mood of the players, and the negative feelings may be more related to losing games than the interaction with the other player itself.

The question *'I felt inclined to work together with the other'* was also added to the questionnaire for *Dilemmas*. Results show that the majority of players (7 out of 12) gave the item a score of 3 or 4, agreeing 'fairly' or 'extremely' with the sentence (see Figure 7.9). The mean score for this item was 2.7, which means that overall, players felt 'fairly' inclined to work together with the other player. However, when compared to the results obtained in *Kessel Run*, there were more 0 and 1 answers

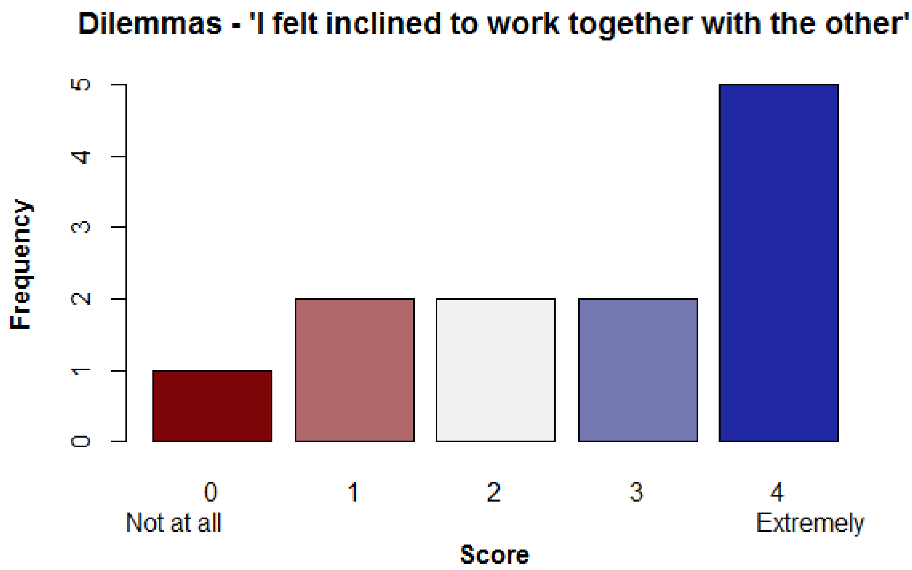


Figure 7.9: Frequency bar plot of answers to the item *'I felt inclined to work together with the other'* for the game *Dilemmas*.

to this item. This may suggest that a small portion of the players did not feel very inclined to work together with the other because they perceived the game as more competitive than cooperative. These results might have been affected by the level of acquaintance of the two participants in each session. In fact, for participants that were paired with strangers, the average answer to this item was 1.5, while for subjects participating with a friend the average answer was 3.8. This inclination to work together with the other is possibly reflected in the strategies used throughout *Dilemmas*.

7.2.3 Event-related potentials to game outcome

As a starting point, EEG signals recorded during the game *Dilemmas* were matched to a similar circumstance in the game *Kessel Run*. Average EEG potentials recorded in the 1 second period prior to the decision key-press in the game *Dilemmas* (for cooperative or defective decisions) were compared to the same time period anticipating a 'Take Over' key-press in the game *Kessel Run* (see 7.10). Grand averaging was performed across 7 subjects, and the mean of the four medial frontal channels Fc1, Fc2, Fz and Cz was extracted. No similarities between the three traces were detected in this time period anticipating a motor action in the channels analysed. The signal is clearly noisier when subjects played *Kessel Run*, due to performing head movements and communicating with the other player. Among the two conditions in *Dilemmas* (cooperated or defected) there are also not any distinct ERPs anticipating the key-press in the analysed region. The four channels of interest cover the medial frontal cortex, with a role in the decision-making process, but in this segment the prominent activity comes from the motor cortex, which may have reduced the signal from our region of interest.

Average EEG potentials recorded during the game *Dilemmas* were compared for several conditions of strategy (cooperative or defective decisions) and outcome (winning or losing each game). Data was band-passed from 1 to 49 Hz and segmented

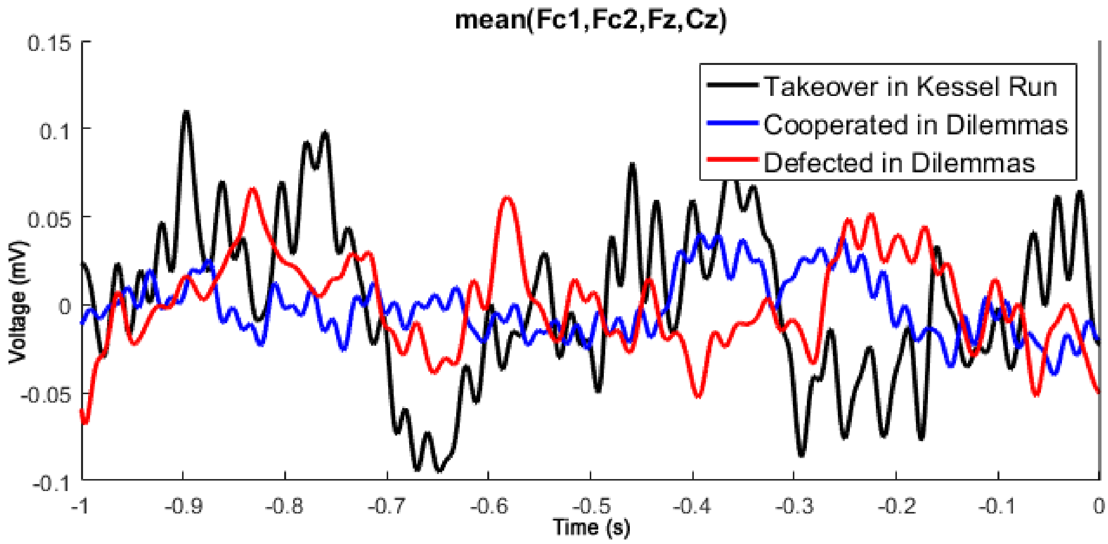


Figure 7.10: Average potential over the four medial frontal channels 1 second before players' button-press to 'Take Over' in *Kessel Run* (black) or key-press to cooperate (blue) or defect (red) in *Dilemmas*.

into trials from -500 ms to 2000 ms related to stimulus presentation of the game outcome.

Figure 7.11 shows the topographic plots of EEG potentials averaged during 100 ms intervals after the game outcome presentation (no conditions selected). All channels were referenced to average and any high variance channels were repaired with the weighted average of the surrounding channels. A strong medial frontal positivity is clearly visible from 200 to 300 ms after stimulus presentation, persisting in the 300 to 400 ms interval, albeit much weaker. This positivity matches the characteristics of the P300 component, both in latency and region involved, and as expected is related to processing of information about rewards or losses.

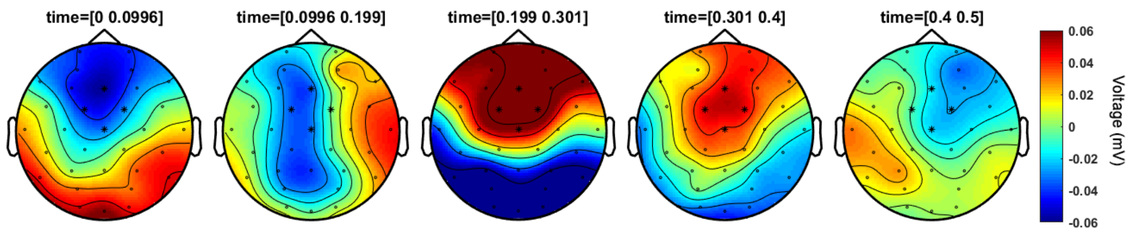


Figure 7.11: Topographic plots of EEG potentials (in mV, frequency range 1 to 49 Hz) after the outcome presentation in *Dilemmas* (grand average across 9 subjects). Baseline was applied from -500 ms to 0 ms prior to stimulus and individual plots correspond to average in 100 ms intervals after stimulus. Channels analysed in this study are highlighted with an asterisk (*).

Average EEG potentials of the four medial frontal channels are represented below, from -200 ms prior to stimulus onset (outcome presentation) to 1000 ms post stimulus. Baselining was performed from -500 ms to 0 ms prior to stimulus. Grand averaging was performed across 7 subjects.

When comparing the two strategy conditions (cooperating or defecting) in the current trial (see Figure 7.12), the P300 is clearly visible from 200 ms to 400 ms after stimulus onset. However, the signal for the 'defect' condition is noisier due to less number of trials. These results alone show no difference in the information processing related to the decision taken earlier in the trial.

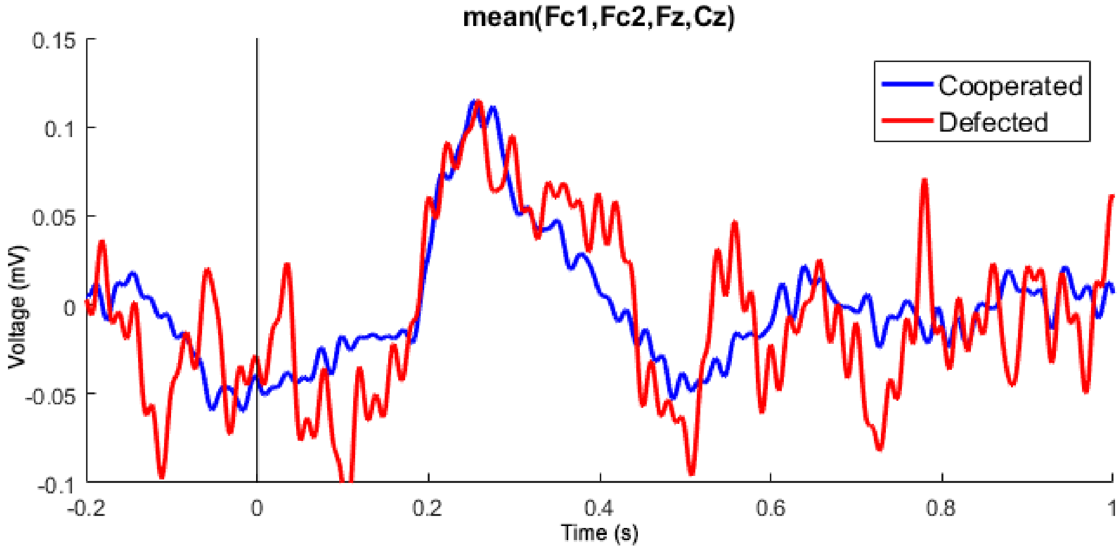


Figure 7.12: Average potential (in mV) over the four medial frontal channels when players cooperated (blue) or defected (red) in the current trial.

When comparing the two strategy conditions in the following trial (see Figure 7.13), ERPs associated to cooperating or defecting in the next trial appear to have different peak latency. The P300 wave for the 'cooperate next' condition peaks at around 250 ms while the wave for the 'defect next' condition peaks at around 350 ms. For both signals the P300 wave lasts for a shorter period, when compared to previous conditions of cooperating or defecting in the current trial.

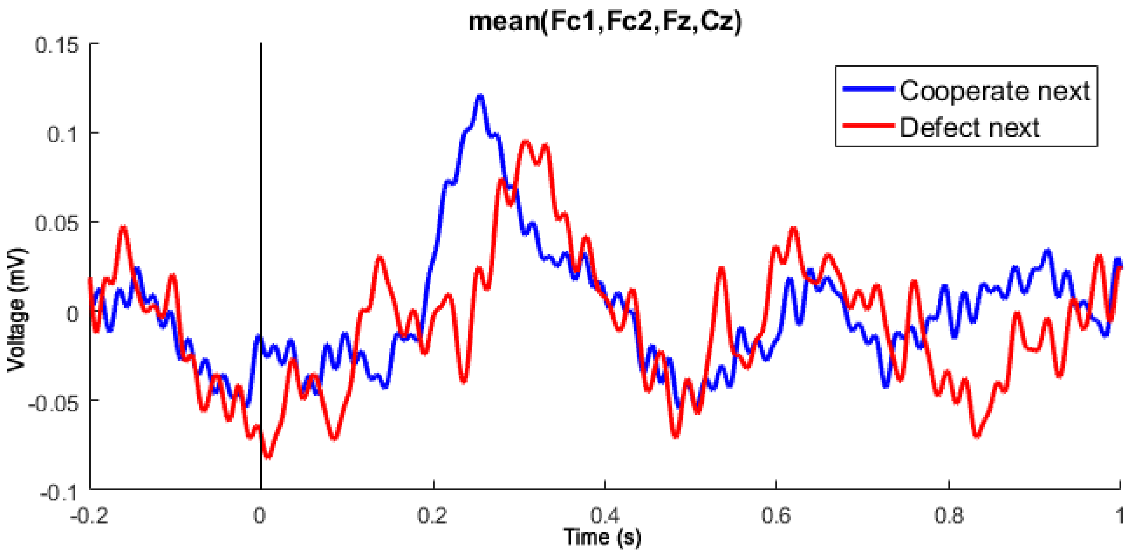


Figure 7.13: Average potential (in mV) over the four medial frontal channels aggregated when players cooperated (blue) or defected (red) in the following trial.

When comparing the two outcome conditions (winning or losing) in the current trial (see Figure 7.14), a similar difference in ERP latency appears to exist. The P300 wave starts earlier for the 'won' condition, at around 200 ms, but slightly later for the 'lost' condition.

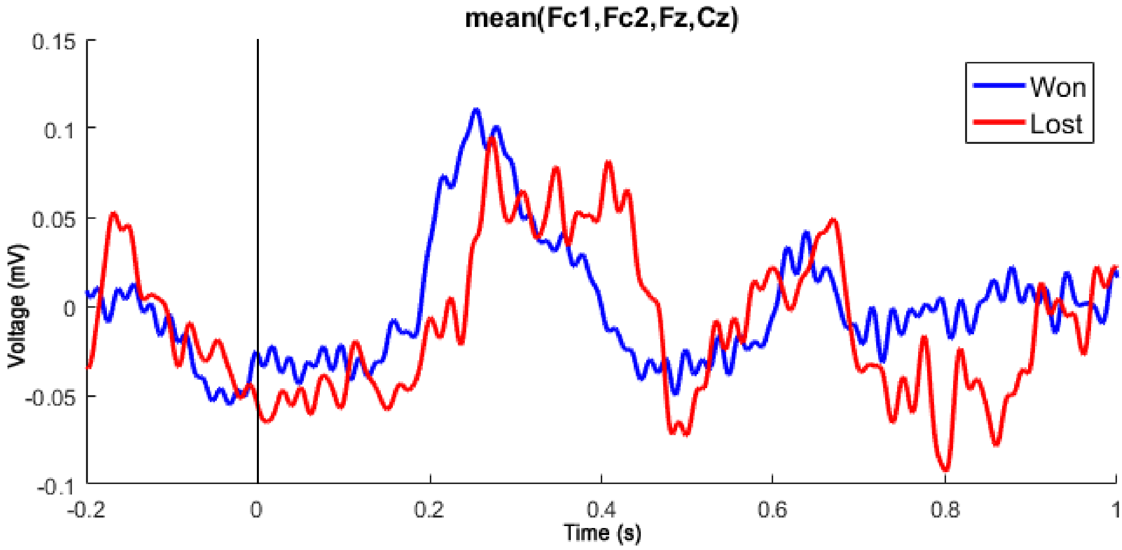


Figure 7.14: Average potential (in mV) over the four medial frontal channels aggregated when players won (blue) or lost (red) in the current trial.

Due to differences in the P300 waves for the two cases analysed above, we decided to study the effect of combinations of both pairs of conditions: strategy (cooperate/defect) and outcome (win/lose). The average potentials over the medial frontal region from 0 ms to 500 ms after stimulus onset are presented in Figure 7.15, for the four new conditions: 'cooperate-win', 'cooperate-lose', 'defect-win' and 'defect-lose'. In Appendix H the detailed signal plots where the statistical comparison between average voltage in different conditions is performed using a T-test ($H_0 : \mu_x = \mu_y$, assuming equal variances) are presented, for the Fc1, Fc2, Fz and Cz channels individually.

For the 'cooperate-lose' condition there is a discernible feedback-related negativity (FRN) from 200 to 250 ms after outcome presentation that is not present (or not so pronounced) for the other three conditions (see Appendix H). Considering the amplitude of the FRN is expected to increase when participants fail to achieve a desired feedback, it is coherent with the situation where participants were expecting to win but unexpectedly lost the round. After cooperating it is normal to expect to win the round since that would be the "fairest" outcome in the point of view of the player. Choosing to defect is a risky strategy that can break the trust between the players, so participants may not be expecting to win the round.

Table 7.5 shows the result of the statistical comparison (T-test p-values) of the several conditions for the 200 to 250 ms interval after stimulus presentation, for the four medial frontal channels analysed. The 'cooperate-win' and 'cooperate-lose' conditions are statistically different for every channel studied in this interval, with smaller p-values for the Fc1 and Fz channels. The 'cooperate-lose' and 'defect-lose' also show differences, for the Fc1 and Fz channels. This may be due to the fact that the other two channels' signals were noisier, in particular the Fc2 channel. In perfect

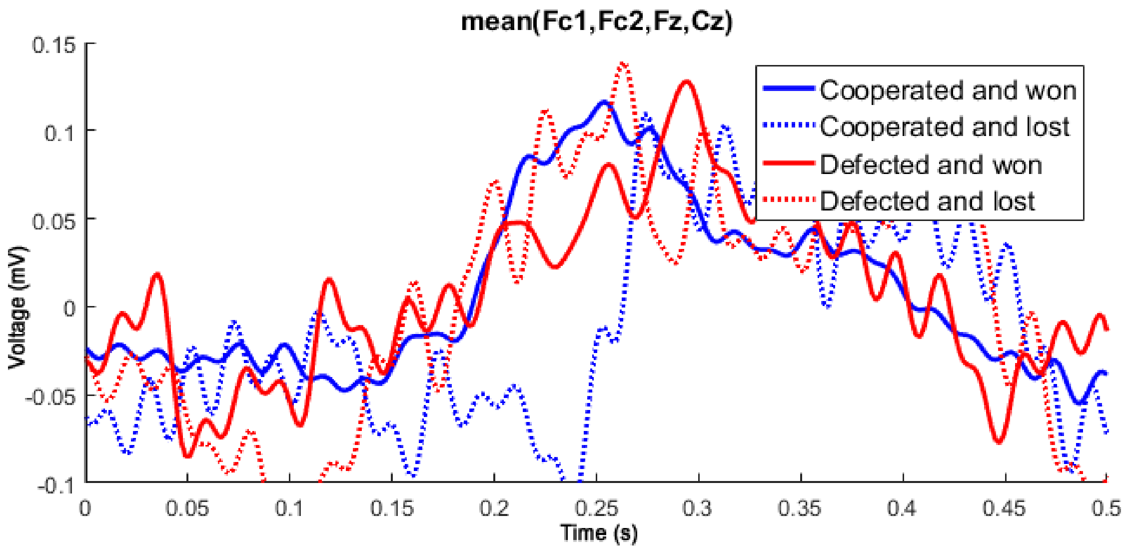


Figure 7.15: Average potential (in mV) over the four medial frontal channels aggregated when players cooperated and won (blue, filled), cooperated and lost (blue, dotted), defected and won (red, filled) and defected and lost (red, dotted).

conditions it is expected this difference exists across all medial frontal locations. The other pairs of conditions compared show no statistical differences.

Table 7.5: Statistical differences (p-values) between average voltage in different conditions in *Dilemmas* per EEG channel for the 200 to 250 ms interval after stimulus onset. Note: $*p < 0.05$; $**p < 0.01$.

Conditions	Fc1	Fc2	Fz	Cz
Cooperate: win vs lose	0.0072**	0.0168*	0.0038**	0.0180*
Defect: win vs lose	0.5871	0.4170	0.5018	0.6291
Win: cooperate vs defect	0.4319	0.3015	0.9859	0.1373
Lose: cooperate vs defect	0.0350*	0.0589	0.0210*	0.1407

The ‘cooperate-lose’ trials seem to correlate to the ‘defect next’ trials (see Figure 7.13), which corresponds to a common strategy used in game theory dilemmas called tit-for-tat, or “equivalent retaliation”. A player using the tit-for-tat strategy will start by cooperating, then subsequently replicates its opponent’s behaviour in the last round of the game. This proved to be a highly effective strategy in iterated social dilemmas, hence why it may have been used by the participants in this study.

In fact, in situations where players cooperated and lost in a given trial, 60% cooperated in the next trial while 40% defected. This percentage is fairly larger than the average defection rate of 26.7% obtained for all the games. A large amount of players adopted this strategy but even though no communication was allowed during *Dilemmas*, strategies were heavily dependent on the acquaintance level of the pair of participants.

8

Discussion

Results of accuracy for the SSVEP-based BCI implemented to control *Kessel Run* were lower than expected for this kind of interaction. The performance may have been impaired because the CCA classification algorithm was designed to issue a game command every 0.15 seconds in order to keep the fast pace of the game. Optimizing the number of samples required to maintain the game pace may improve the overall accuracy of the system. The player reported experience can, nonetheless, be considered quite positive. We believe that following the design requirements in *Kessel Run* helped in creating an enjoyable and positive experience to its players, despite struggling with the game controls.

Studying ERPs during a multiplayer BCI game like *Kessel Run* proved unsuccessful. Since *Kessel Run* also served a different research project with the aim of studying emotion elicitation in a BCI game, we could only include one time-locked task, the 'Take Over' mechanic (activated with a physical button-press). However, this game mechanic did not reflect a clear cooperation or defection between co-players such as the strategies used in a typical game theory dilemma. The EEG recordings were also too noisy to extract any information on potentials anticipating decision-making, which might be solved by applying different methods of artefact detection such as Independent Component Analysis (ICA). In summary, *Kessel Run* might not have been the best game to explore cooperative behaviours using neurophysiological measures. A BCI game with turn-based actions controlled with the P300 paradigm would probably be the most similar game to the iterated social dilemmas and might provide the best comparison conditions between games in order to meet the established goals.

The game *Dilemmas*, on the other hand, served its purpose as a controlled setting that allowed us to gather brain activity data during cooperative and defective decisions. Combining the game theory dilemmas with neurophysiological measures, we have successfully found event-related components P300 and FRN comparable to previous research, using the iterated Chicken game [75] and the prisoner's dilemma [6]. Using different games may not provide the best results, as the cooperation rates differ a lot from game to game (Table 7.4). In fact, current research in decision-making usually uses only one kind of social dilemma per experiment, with a greater number of iterations. We opted to limit each game to 5 rounds to keep the play time shorter and used several different games to keep the experience enjoyable for the players and not monotonous. Furthermore, decision-making experiments typically consist in a subject playing against a virtual partner, with automated behaviours determined by the computer. This work was an attempt at studying interactions between two co-located subjects playing against each other, with no communication allowed between them, which may cause different cognitive responses due to behavioural involvement. Even though results from the iterated social dilemmas were consistent with the literature, we believe the gathered dataset can be explored even further.

9

Conclusion

This thesis had the main goal of exploring how neurophysiological measures related to decision-making can be collected and applied in a multiplayer BCI game. Mainly motivated by the current increase in popularity of BCI applications for healthy users, we proposed to design a BCI game that provided an immersive and enjoyable experience for its players. Additionally, because we find that multi-brain games are one of the most interesting outlooks of this technology, we opted to develop a cooperative game for two players. Inspired by the current trend of bringing more natural interaction modes to the gaming industry, we intended to explore what measures obtained from the EEG already used in the BCI system can be implemented in a multiplayer game, whether to control or adapt the game based on player behaviour.

In order to reach our research goals, two games were developed: *Kessel Run*, a cooperative BCI game based on the SSVEP paradigm, and *Dilemmas*, a set of five iterated social dilemmas where two players compete or collaborate with each other. We set up an experiment where participants played both games sequentially. The BCI performance during *Kessel Run* was assessed, as was the gaming and social experience of participants, relying on validated questionnaires filled after each game session. A time-locked analysis of the brain activity recorded during both games was performed, where we looked at ERPs originated from the medial frontal cortex, namely the P300 and FRN components.

The performance of the SSVEP paradigm BCI was lower than expected, reaching only a maximum accuracy of 79% with average overall accuracy equal to 55% for a 33% chance level. The two factors identified that most influenced the performance were the variability in SSVEP frequency detection between subjects and the lack of darkness in the experiment laboratory. Participants had generally lower classification scores for the 15 Hz frequency than the 12 Hz frequency, possibly due to 12 Hz being in the dominant alpha range. Choosing tailored frequencies for each individual subject may have improved performance, as accuracy in a CCA-based detection method differs depending on frequencies used. Even though it serves as proof-of-concept for a multiplayer SSVEP game, a different, more intuitive paradigm such as movement imagery may be more suitable for *Kessel Run*, allowing players to keep their gaze on the screen at all times.

The reported player experience was overall positive, despite the difficulty in controlling the game with the SSVEP paradigm. Players only felt slightly competent during the game but still achieved a state of Flow. This might have been due to the collaborative strategy developed by some players to circumvent bad SSVEP classification, where the player with better control would steer the spaceship while the co-player gave directions on where to go. On the social presence assessment, players reported that they empathized with each other, partially due to having to communicate in order to win the game. Because 8 out of 12 players felt 'fairly' to 'extremely' inclined to work together with the other, we can say the cooperative game design rules were successfully implemented and the game provided a positive social experience.

Regarding the exploration of ERPs during game play, we started by looking at the data collected during *Kessel Run*. Recordings turned out to be too noisy to extract any information on potentials anticipating decision-making. Furthermore, we could only analyse data time-locked to the 'Take Over' mechanic, which was not frequently used by many players. The game mechanics and controls did not favour the collection of EEG data for this decision-making analysis, since players were encouraged to talk and move their head to look at the light sources in order to control the game. Implementing a different, more passive interaction paradigm may allow the study of decision-making in this BCI game.

On the game *Dilemmas*, the social presence reported by players was slightly different from *Kessel Run*, as a result of the contrasting nature of the game. In this game, the level of acquaintance of the two players participating in each session heavily influenced how they played the game. Participants paired with a stranger felt less inclined to cooperate, and took a more competitive approach to the game, feeling less empathy for the other player. Players also reported more negative feelings while playing *Dilemmas* than *Kessel Run*, although these could be linked to losing rounds rather than due to the interaction with the co-player. Tit-for-tat was the most common strategy adopted by players, meaning that they generally started by cooperating and subsequently replicate the decision made by the opponent in the last round.

In contrast to *Kessel Run*, we have successfully identified two ERP components time-locked to the *Dilemmas* round outcome presentation: the P300 and the FRN. The controlled setting of this game facilitated the detection of a strong medial frontal positivity was observed in topographic maps, for the channels Fc1, Fc2, Fz and Cz. This positivity matched the characteristics of the P300 component, a positive deflection in the ERP, related to processing of information about rewards or losses. The P300 was observed in topographic plots and time-locked ERPs between 200 and 500 ms after the presentation of game outcomes to the players. After identifying differences in the ERP among the trials were players cooperated or defected in the next trial, the feedback-related negativity component was also detected, although limited to trials where players cooperated and lost the round. The FRN was identified from 200 to 250 ms after stimulus onset. The conditions where the FRN was found correspond to the tit-for-tat strategy, a common strategy among players, particularly for pairs of strangers participating in the experiment. A player that cooperates and receives a negative outcome (loses the round) is more likely to defect in the next round, repeating their opponents' earlier behaviour.

The insights gathered in this study helped us understand the difficulty of collecting EEG data during an active BCI game play experience. To achieve proper ERP detection while playing a game, more robust algorithms must be developed in order to overcome the presence of artefacts. Nevertheless, the applications of neural correlates to decision-making in games seem promising, particularly in serious games and multi-brain games.

9.1 Future work

The main advantage for any future work involving the applications developed is the high flexibility of the system design, implemented with BCI2000. The current integrated system allows the BCI game *Kessel Run* to be played using several alternative acquisition systems, such as Emotiv EPOC. The game can also be used in a single-player set-up, in a local or remote set-up, and can run in a different computer than the one doing the acquisition, decreasing the computation costs in that machine.

In order to enhance the BCI gaming experience, we can either improve the SSVEP classification performance or implement a distinct interaction paradigm. The current SSVEP classification is fast with low computation costs, suiting the fast dynamics of the game, but may not give enough time for the SSVEP to reach a steady state in the EEG signal. Increasing the number of samples used for each classification may improve BCI control without affecting the game pace. Another option is to implement a more intuitive control paradigm, such as movement imagery, that does not require players to shift focus from the game.

Even though there is room for improvement in this work, the dataset collected during this experiment is unquestionably interesting. Despite the strong artefacts present in the data, we could try studying oscillatory activity or inter-brain EEG synchrony between the co-players during *Kessel Run* game play, as there was not much chance to analyse time-locked events. The game *Dilemmas* may be used to study the wording and context of the game theory dilemmas and its effect on cooperation rates, as well as the effect of acquaintance level of the subjects participating.

As a future prospect it would be appealing to analyse a subject's particular brainwaves as a means to decode future decisions, and in that way improve communication, collaboration and team dynamics amongst a group of people.

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Appendix A

Call for participants

Want to play a game with your brain signals?

What?

We're looking for participants to take part in a Brain-Computer Interface experiment in which you play a **multiplayer game using only your brain signals as a controller**. The game is multiplayer, which means **you can bring a friend with you and play together**!

When? Where?

The experiment takes place in Zilverling building at University of Twente, and takes approximately 1 hour. You can choose to participate when it is more convenient to you (and your friend).

How?

You can participate by filling the form at *goo.gl/forms/TWBQgmblwJBB3yQu2*

Attention: the experiment is for a multiplayer game, which means you should bring a friend to play with you. In case you cannot bring someone, let us know so we can pair individual participants together ☺

Questions? *Any burning questions can be sent to* i.palmadelimaecruz@student.utwente.nl

Appendix B

Informed Consent Form

UNIVERSITY OF TWENTE.

Human Media Interaction

Informed Consent Form

Title of Study: *User affective state and cooperative decision making in a multiplayer BCI game*
Investigators:

Inês Cruz	**Dept:**	HMI	**Email:**	ines.cruz@campus.ul.pt
Carlos Moreira	**Dept:**	HMI	**Email:**	cfmoreira@campus.ul.pt

Introduction

Before agreeing to participate in this research study, it is important that you **read the following explanation of this study**. This statement describes the purpose, procedures, risk, discomforts, and precautions of the experiment. Feel free the ask for clarification if you encounter any term or expression that you do not understand.

Your participation is voluntary; you are free to withdraw consent in this project at any time without penalty and without giving a reason.

Purpose of Study

This is a multi-purpose study that investigates the different affective states a player experiences during a realistic gameplay using a multiplayer brain-computer interface system. Moreover, it investigates the brain activity patterns related to the players' cooperative/defective actions.

Description of the Study Procedures

If you agree to be in this study, you will be asked to do the following things:

Before the experiment, you will complete a questionnaire to provide some demographic information;

Afterwards, the BioSemi cap and electrodes will be mounted on your head. To ensure good connectivity between your brain activity and the electrodes, a **gel will be applied to your scalp**. This leaves a residue on your hair. **We provide towels and shampoo after the experiment**, but feel free to bring your own toiletries.

Meanwhile, the game will be explained and you will have some time to practice and become familiar with the gameplay. Note that the game makes use of **flickering lights**. **Participants with any neurological disorder (epilepsy in particular) cannot participate in the study.**

During the experiment you will play the game with another person and fill in questionnaires. After the game, two quick additional tests will be performed.

The whole experiment, including preparation of the setup, game playing, and questionnaires will last less than 2 hours. **You can ask for breaks** before and in between game levels.

Risks/Discomforts of Being in this Study

There are no reasonable foreseeable (or expected) risks for people with no neurological health conditions.

Confidentiality

You will have your brain activity recorded via the BioSemi system that you will wear on your head. Your keyboard activity will be recorded as well, and some behavioral observations (such as talk between players) will be documented. All the recorded data and the results of measurements may be used for research and publications. The data will be anonymized and may be made public for research purposes.

Right to Ask Questions and Report Concerns

You have the right to ask questions about this research study and to have those questions answered before, during or after the research.

If you have any further questions about the study, at any time feel free to contact one of the investigators aforementioned.

Consent

I have read the foregoing information, or it has been read to me. I have had the opportunity to ask questions about it and any questions I have been asked have been answered to my satisfaction. I consent voluntarily to be a participant in this study and state I have no known neurological disorder.

Subject's Name: ______________________

Subject's Signature: ______________________ Date: ____________

Investigator's Signature: ______________________ Date: ____________

A copy of this ICF will be provided to the participant at his request.

Appendix C

Experimental protocol

Protocol for Kessel Run Experiment

0. Send consent form via e-mail to the subjects prior to experiment

1. Have the subjects read and sign the consent form, and fill the demographic google form
   - **a. Make sure a subject ID/player is correct for both participants!**

2. Briefly explain what the experiment is about, what will happen and how long it should take

3. Couple both participants with BioSemi
   - **a.** Player 1 should have GSR and Plethysmograph sensors as well (Inês' computer).
   - **b.** Check ActiView electrode offset is under +-20mV and signal is good
   - **c.** Instruct player 1 to move sensor hand as little as possible

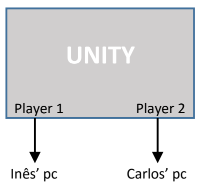
4. In ActiView (in each computer) run the performance test
   - **a.** Ensure trigger serial cable is connected
   - **b.** Key *F1* for looking up, *F2* for looking center, *F3* for looking down
   - **c. START WITH LOOKING UP AFTER 5 SECONDS OF RECORDING**
   - **d.** Record for 80 seconds

5. Start fieldtrip buffer with the right config.txt file

```
> cd C:\Program Files (x86)\MATLAB\R2015b\toolbox\fieldtrip-20160414\realtime\bin\win32
> biosemi2ft config.txt out -
```

6. Start BCI200 from appropriate batch

7. Insert player ID in folder
   - **a.** Play 4 runs of Easy level, and 4 runs of Hard level
   - **b.** After each run, ask to fill in affective questionnaire
   - **c. Always start BCI2000 before game level begins**
   - **d. Always suspend BCI2000 after game ends**



8. Close Unity before closing BCI2000

9. Ask to fill in Game Experience part of the questionnaire

10. Open BCI2000 with prisoners' dilemma batch

11. Open Unity prisoners' dilemma game
   - **a. Always start BCI2000 before game begins**
   - **b. Always suspend BCI2000 after game ends**

12. Close Unity before closing BCI2000

13. Ask to refill in Game Experience part of the questionnaire

Appendix D

Subject questionnaires

Demographic Questions

*Required

1. **Please insert subject ID** *
   First and last name initials and date (dd-mm-yyyy), separated by -. (e.g. JS-25-07-2016)

2. **Select player** *
   Mark only one oval.
   - ◯ Player 1
   - ◯ Player 2

3. **Age** *

4. **Gender** *
   Mark only one oval.
   - ◯ Male
   - ◯ Female

5. **Eyesight** *
   Mark only one oval.
   - ◯ Normal
   - ◯ Corrected to normal
   - ◯ Impaired

6. **Handedness** *
   Mark only one oval.
   - ◯ Left-handed
   - ◯ Right-handed
   - ◯ Ambidextrous

7. **Computer usage** *
Mark only one oval.

- Daily
- Weekly
- Monthly
- Less than once a month
- Never

8. **Gaming experience** *
How often do you play digital (computer, console, mobile) games?
Mark only one oval.

- Daily
- Weekly
- Monthly
- Less than once a month
- Never

9. **BCI experience** *
How many times have you used a brain-computer interface technology before?
Mark only one oval.

- Three or more
- Two
- One
- None

10. **Do you have any neurological (or other relevant) diseases?** *
Mark only one oval.

- Yes *Skip to question 11.*
- No *Skip to question 12.*

Relevant diseases

11. **Which neurological (or other relevant) diseases do you have?**

Game Experience Questionnaire

Please fill in this questionnaire only after you are finished with playing the game.

12. **Game Experience Module** *

Please indicate how you felt while playing the game for each of the items:
Mark only one oval per row.

	Not at all	Slightly	Moderately	Fairly	Extremely
I felt annoyed					
I felt happy					
I was good at it					
I felt irritable					
I felt good					
I had to put a lot of effort into it					
I thought it was fun					
I found it tiresome					
I lost track of time					
I was fully occupied with the game					
I felt competent					
I enjoyed it					
I felt bored					
I felt challenged					
I was deeply concentrated in the game					
I felt pressured					
It gave me a bad mood					
I felt successful					
I felt frustrated					
I thought it was hard					

13. **Social Presence Module** *

Please indicate how you felt while playing the game for each of the items:
Mark only one oval per row.

	Not at all	Slightly	Moderately	Fairly	Extremely
I felt jealous about the other					
I was influenced by the other's moods					
I empathized with the other					
I felt schadenfreude (malicious delight)					
What I did affected what the other did					
My actions depended on the other's actions					
What the other did affected what I did					
I felt connected to the other					
I admired the other					
When I was happy, the other was happy					
I felt revengeful					
The other paid close attention to me					
When the other was happy, I was happy					
I influenced the mood of the other					
I paid close attention to the other					
I felt inclined to work together with the other					
I found it enjoyable to be with the other					
The other's actions were dependent on my actions					

Game Theory Questionnaire

Please fill in this questionnaire after you finish the Game Theory module.

14. **Social Presence Module** *

Please indicate how you felt while playing the game for each of the items:
Mark only one oval per row.

	Not at all	Slightly	Moderately	Fairly	Extremely
I felt connected to the other	◯	◯	◯	◯	◯
The other paid close attention to me	◯	◯	◯	◯	◯
I empathized with the other	◯	◯	◯	◯	◯
What the other did affected what I did	◯	◯	◯	◯	◯
The other's actions were dependent on my actions	◯	◯	◯	◯	◯
I felt inclined to work together with the other	◯	◯	◯	◯	◯
I paid close attention to the other	◯	◯	◯	◯	◯
My actions depended on the other's actions	◯	◯	◯	◯	◯
I admired the other	◯	◯	◯	◯	◯
When I was happy, the other was happy	◯	◯	◯	◯	◯
I found it enjoyable to be with the other	◯	◯	◯	◯	◯
What I did affected what the other did	◯	◯	◯	◯	◯
I influenced the mood of the other	◯	◯	◯	◯	◯
I felt schadenfreude (malicious delight)	◯	◯	◯	◯	◯
I felt jealous about the other	◯	◯	◯	◯	◯
I was influenced by the other's moods	◯	◯	◯	◯	◯
I felt revengeful	◯	◯	◯	◯	◯
When the other was happy, I was happy	◯	◯	◯	◯	◯

Appendix E

Game Experience Questionnaire results for *Kessel Run*

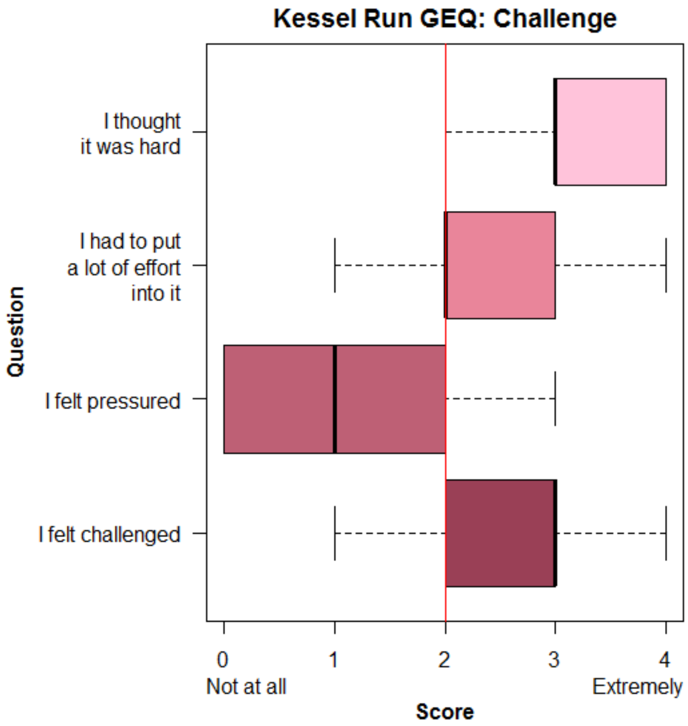


Figure E.1: Box plots for the Game Experience Questionnaire results, in the Challenge category.

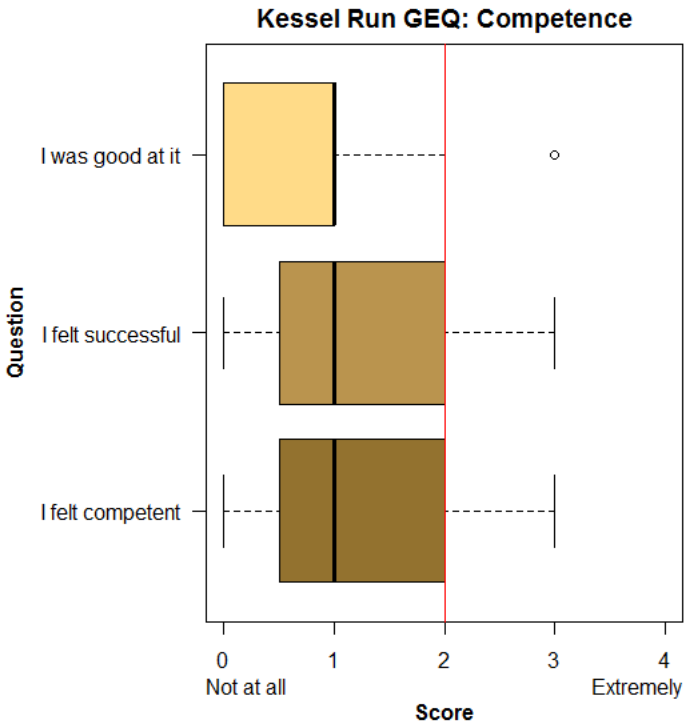


Figure E.2: Box plots for the Game Experience Questionnaire results, in the Competence category.

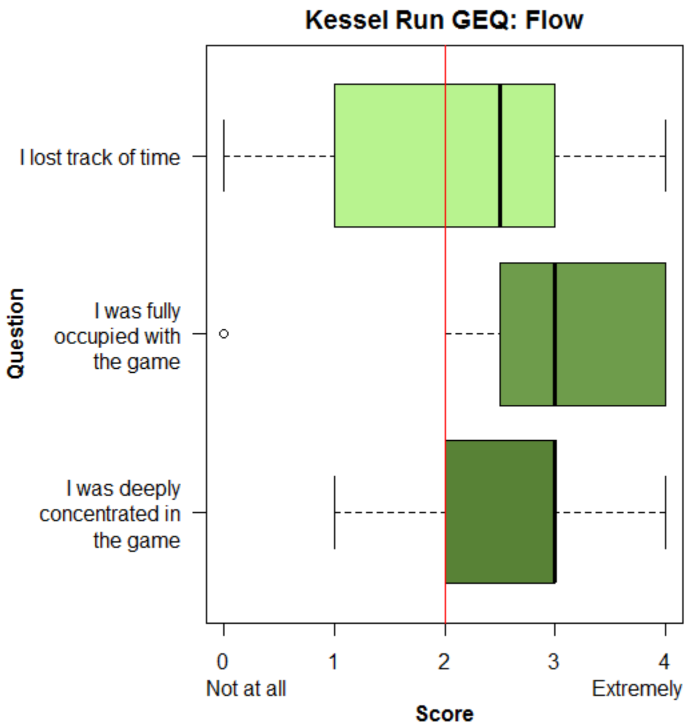


Figure E.3: Box plots for the Game Experience Questionnaire results, in the Flow category.

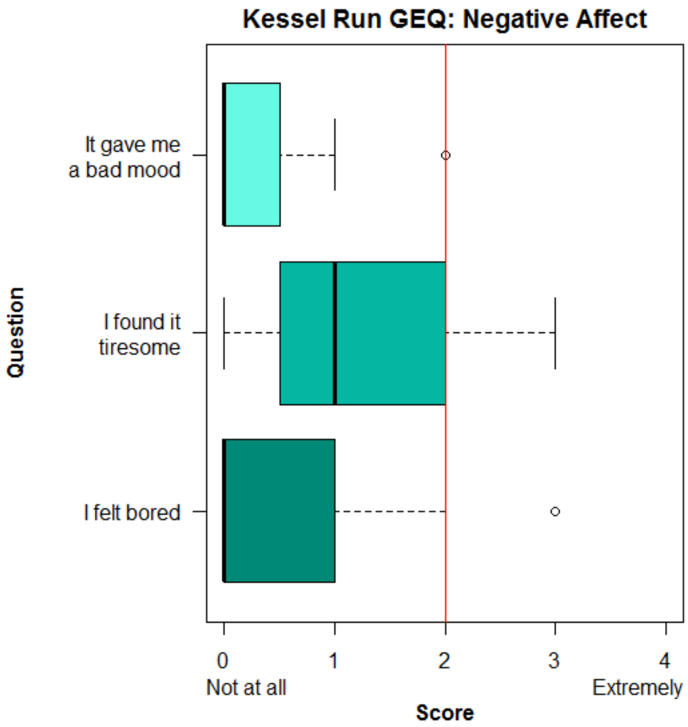


Figure E.4: Box plots for the Game Experience Questionnaire results, in the Negative Affect category.

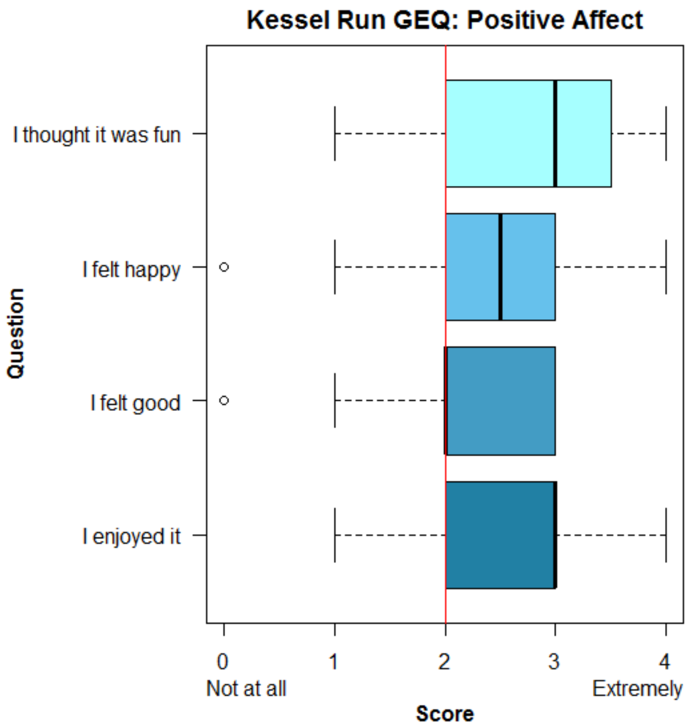


Figure E.5: Box plots for the Game Experience Questionnaire results, in the Positive Affect category.

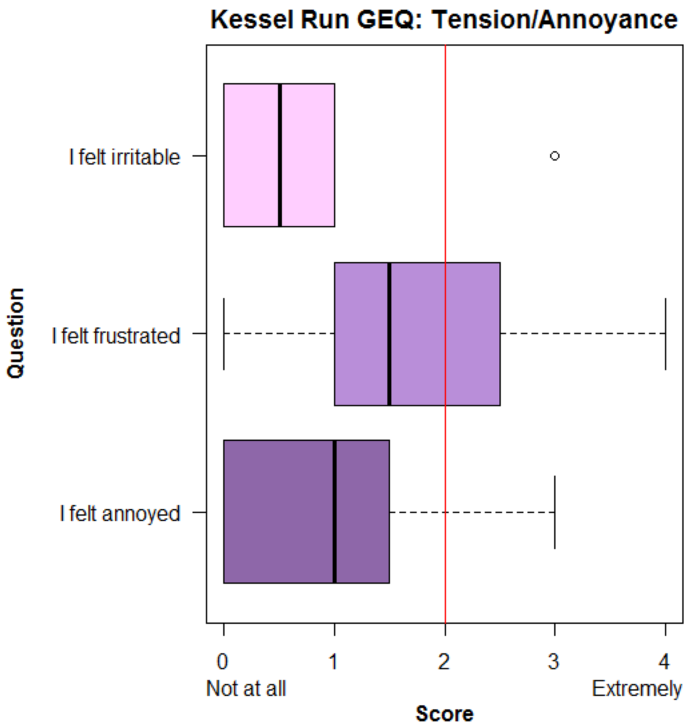


Figure E.6: Box plots for the Game Experience Questionnaire results, in the Tension/Annoyance category.

Appendix F

Social Presence Questionnaire results for *Kessel Run*

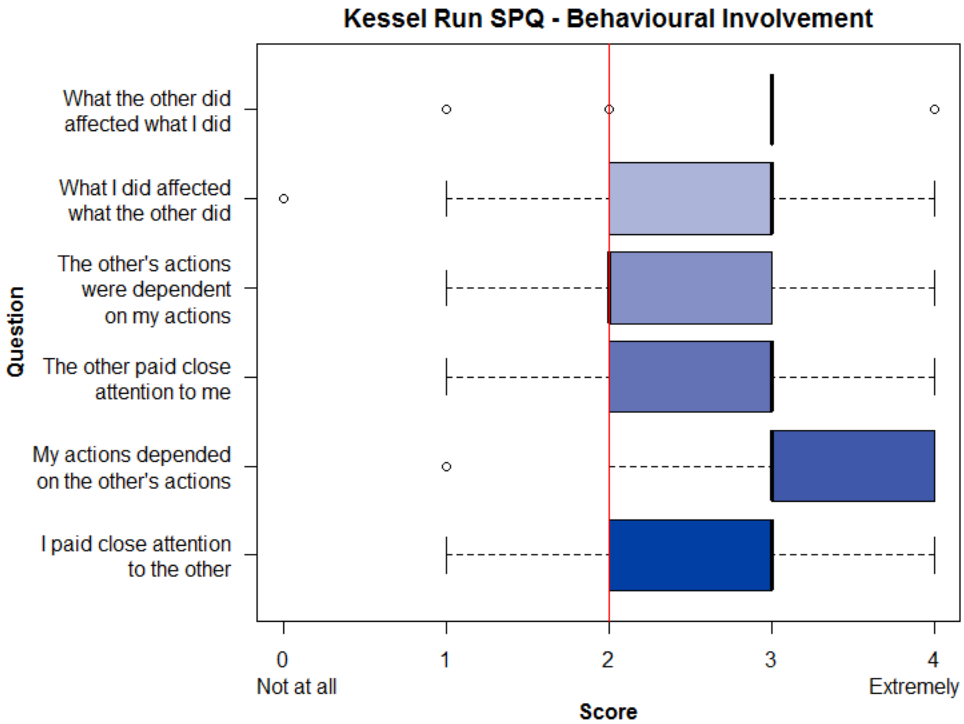


Figure F.1: Box plots for the Social Presence Questionnaire results, in the Behavioural Involvement category.

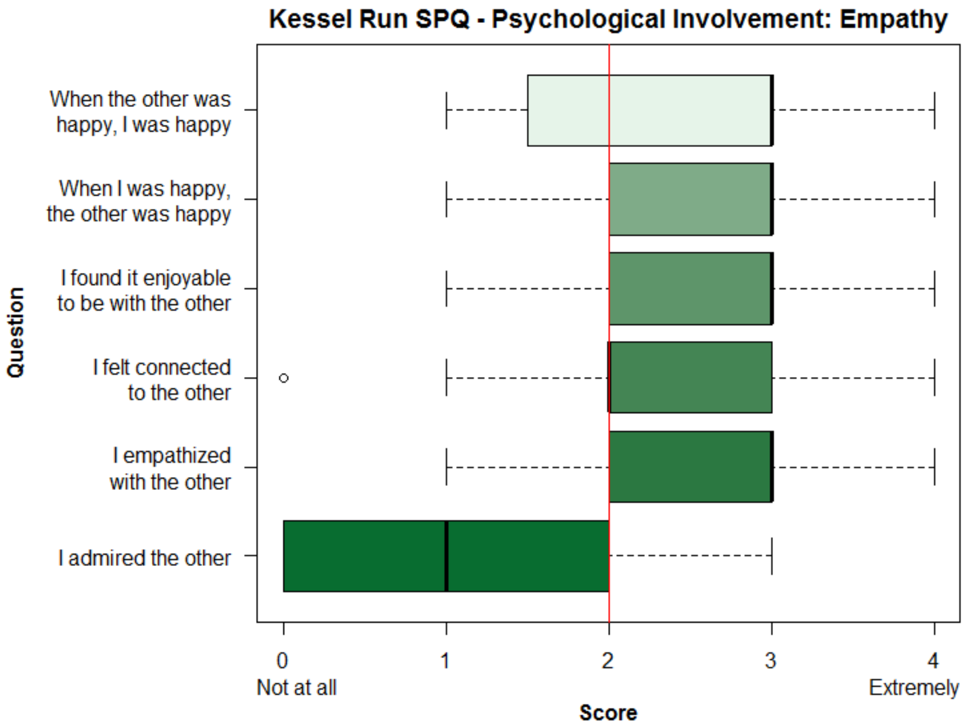


Figure F.2: Box plots for the Social Presence Questionnaire results, in the Psychological Involvement - Empathy category.

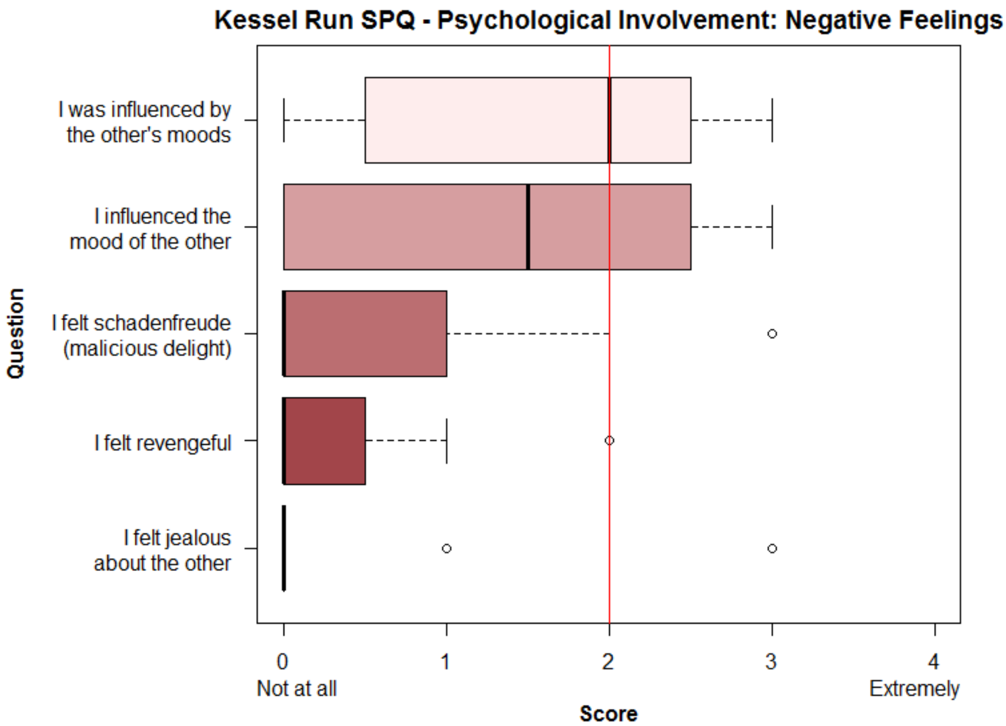


Figure F.3: Box plots for the Social Presence Questionnaire results, in the Psychological Involvement - Negative Feelings category.

Appendix G

Social Presence Questionnaire results for *Dilemmas*

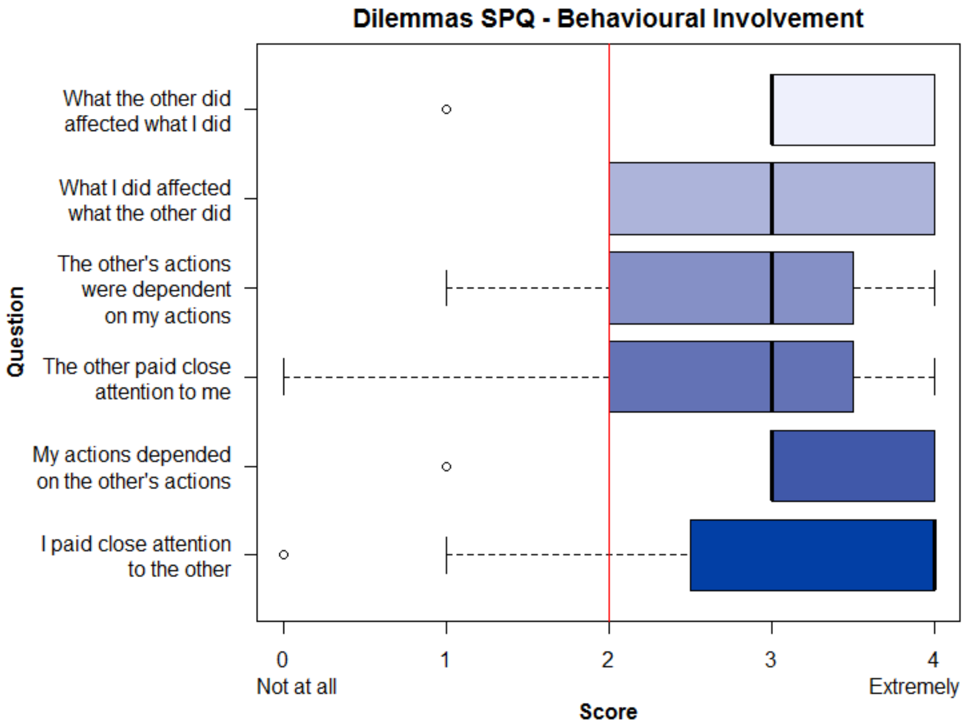


Figure G.1: Box plots for the Social Presence Questionnaire results, in the Behavioural Involvement category.

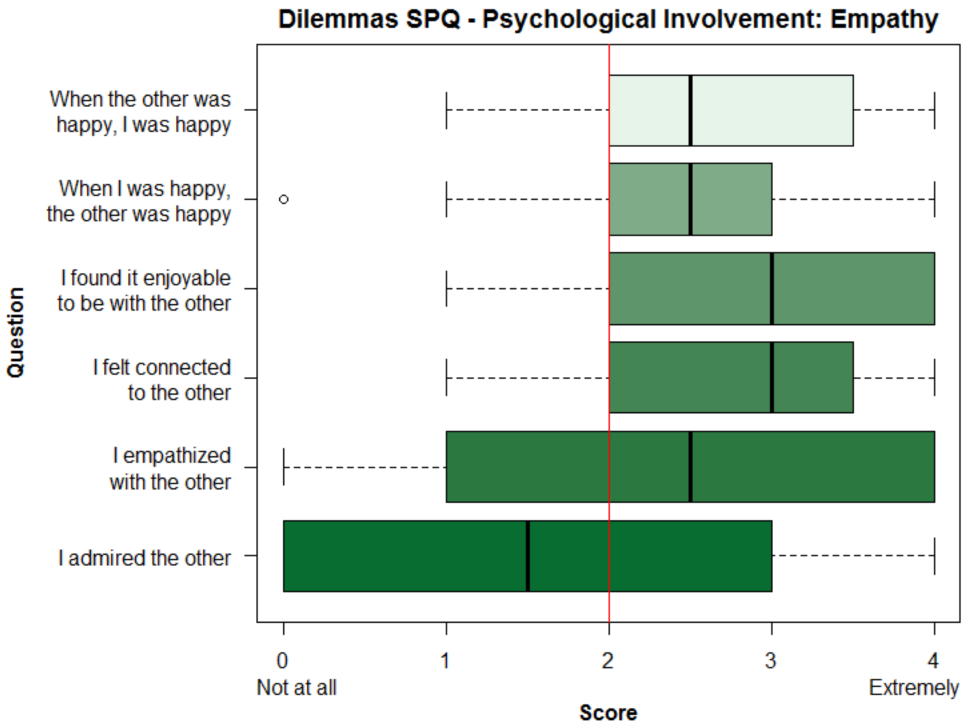


Figure G.2: Box plots for the Social Presence Questionnaire results, in the Psychological Involvement - Empathy category.

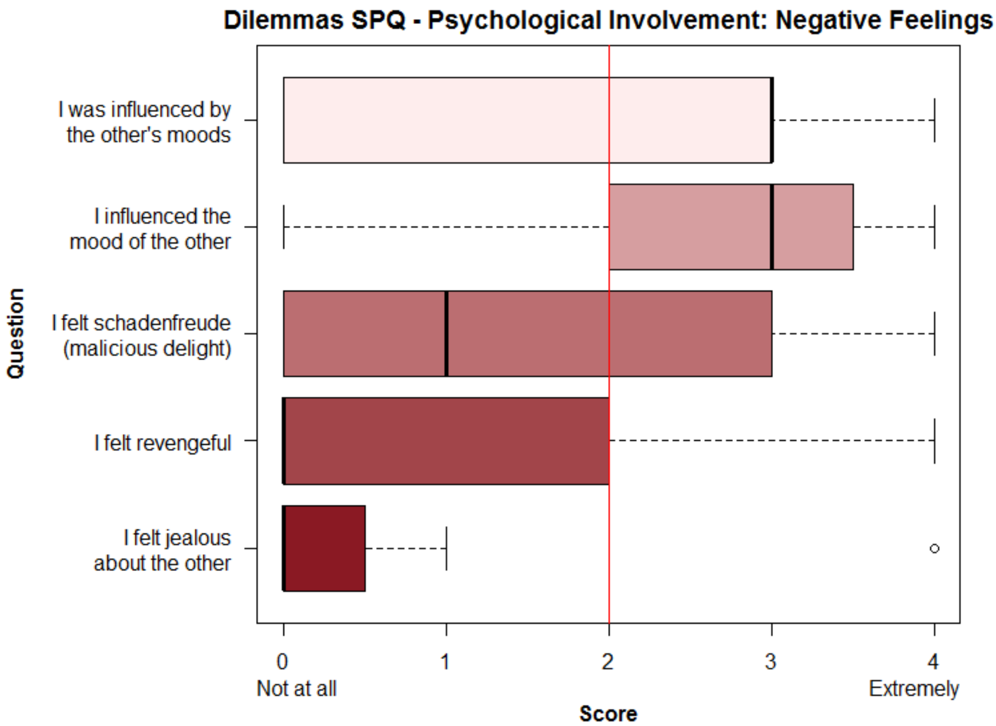


Figure G.3: Box plots for the Social Presence Questionnaire results, in the Psychological Involvement - Negative Feelings category.

Appendix H

Strategy-outcome ERPs for the medial frontal channels

Average EEG potentials over the four medial frontal channels (Fc1, Fc2, Fz and Cz) for the different strategy-outcome conditions in the *Dilemmas* game. The time intervals in orange indicate statistically significant differences (p-value < 0.05) between the two conditions plotted, at that interval.

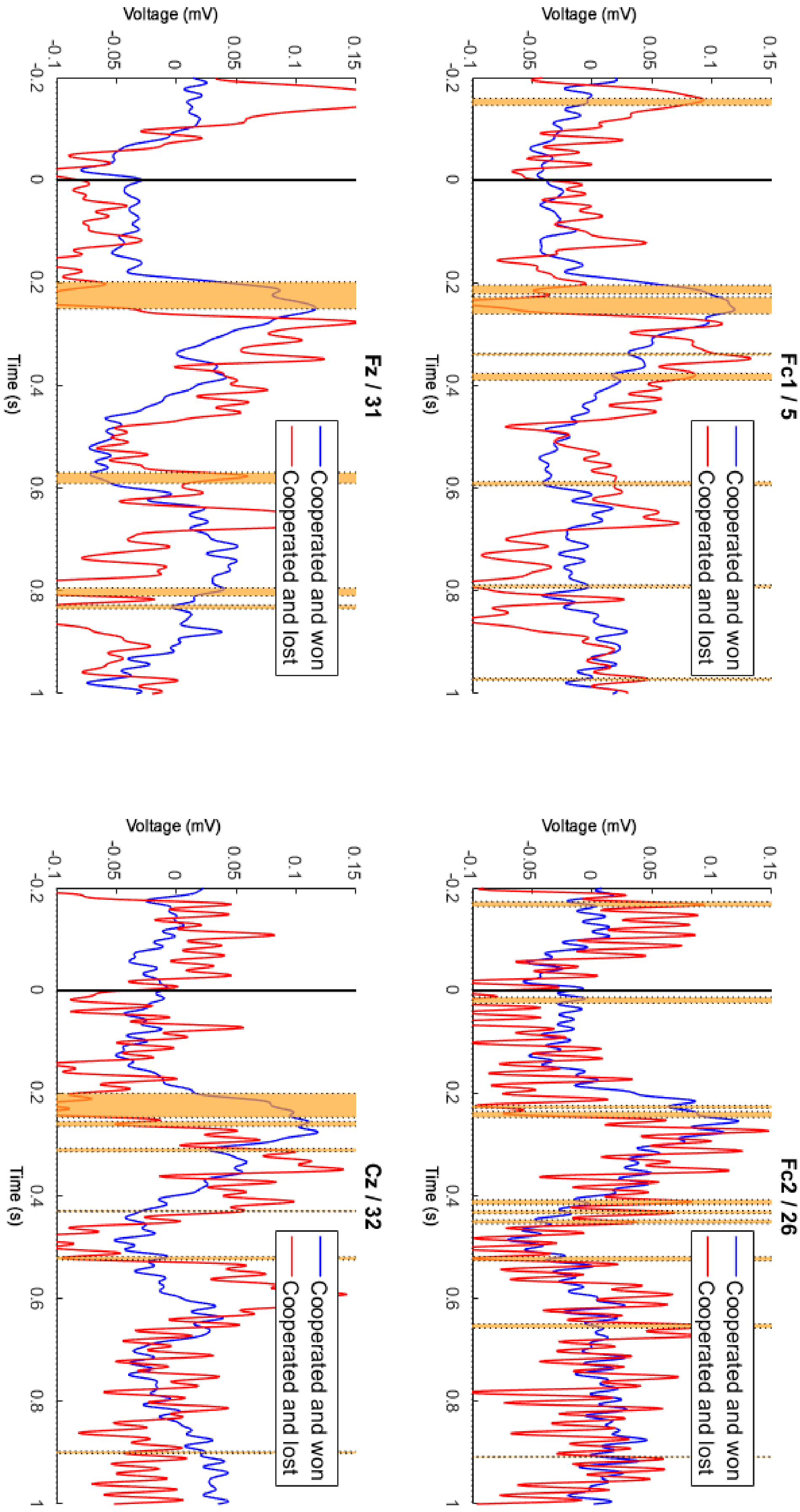


Figure H.1: Comparison of average potential for trials where players won or lost the current game after having cooperated.

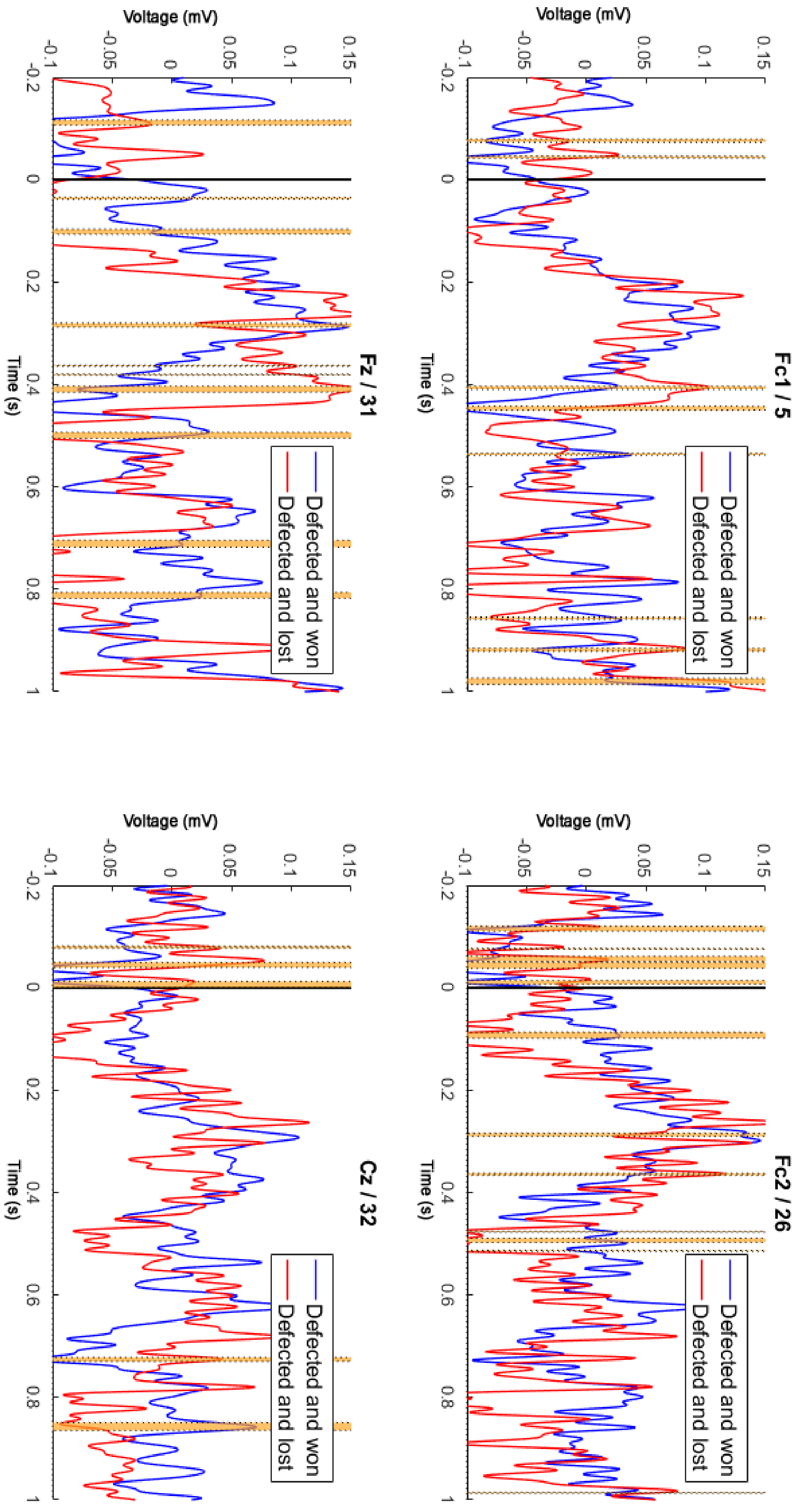


Figure H.2: Comparison of average potential for trials where players won or lost the current game after having defected.

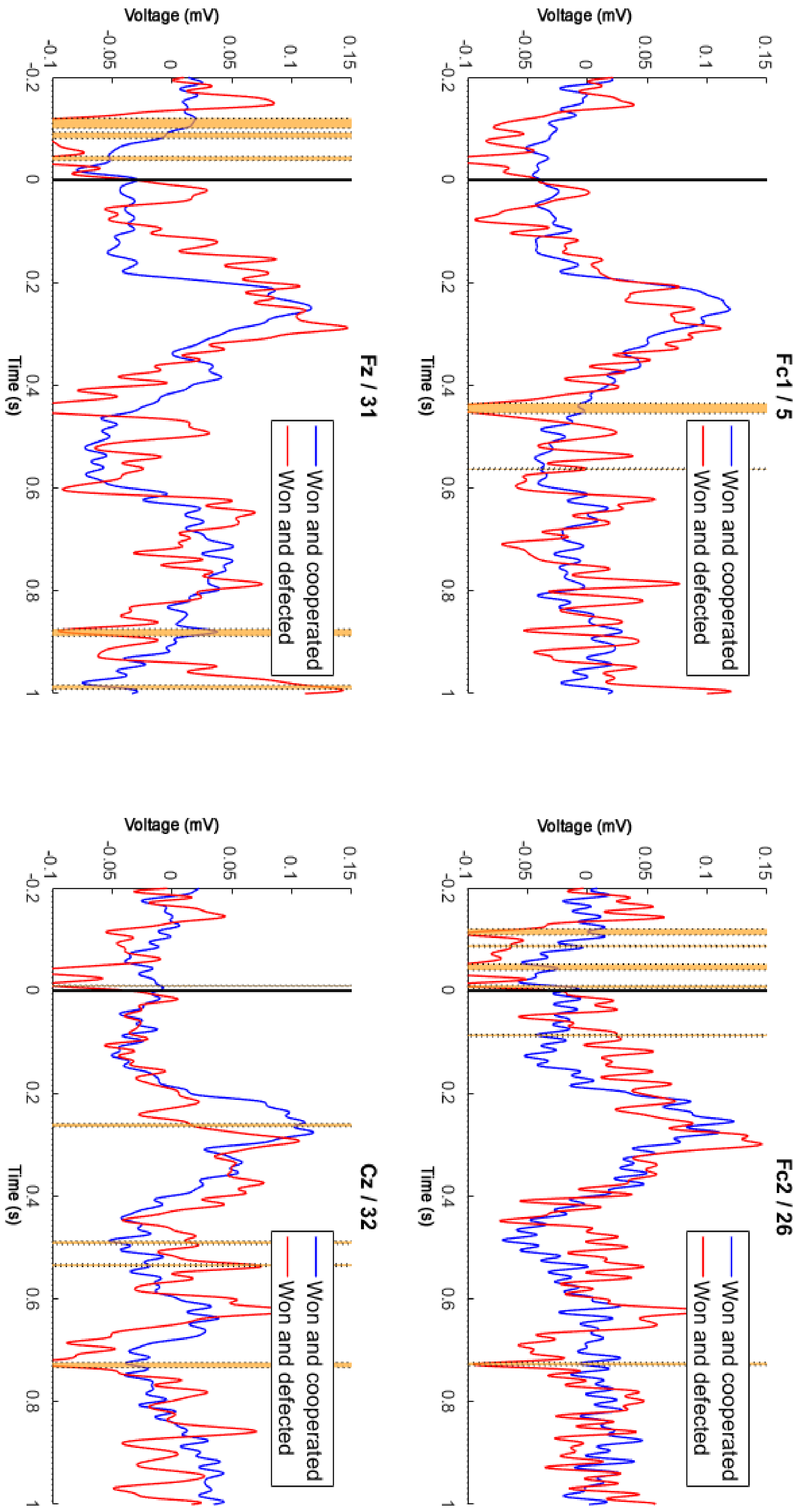


Figure H.3: Comparison of average potential for trials where players won the current game after having cooperated or defected.

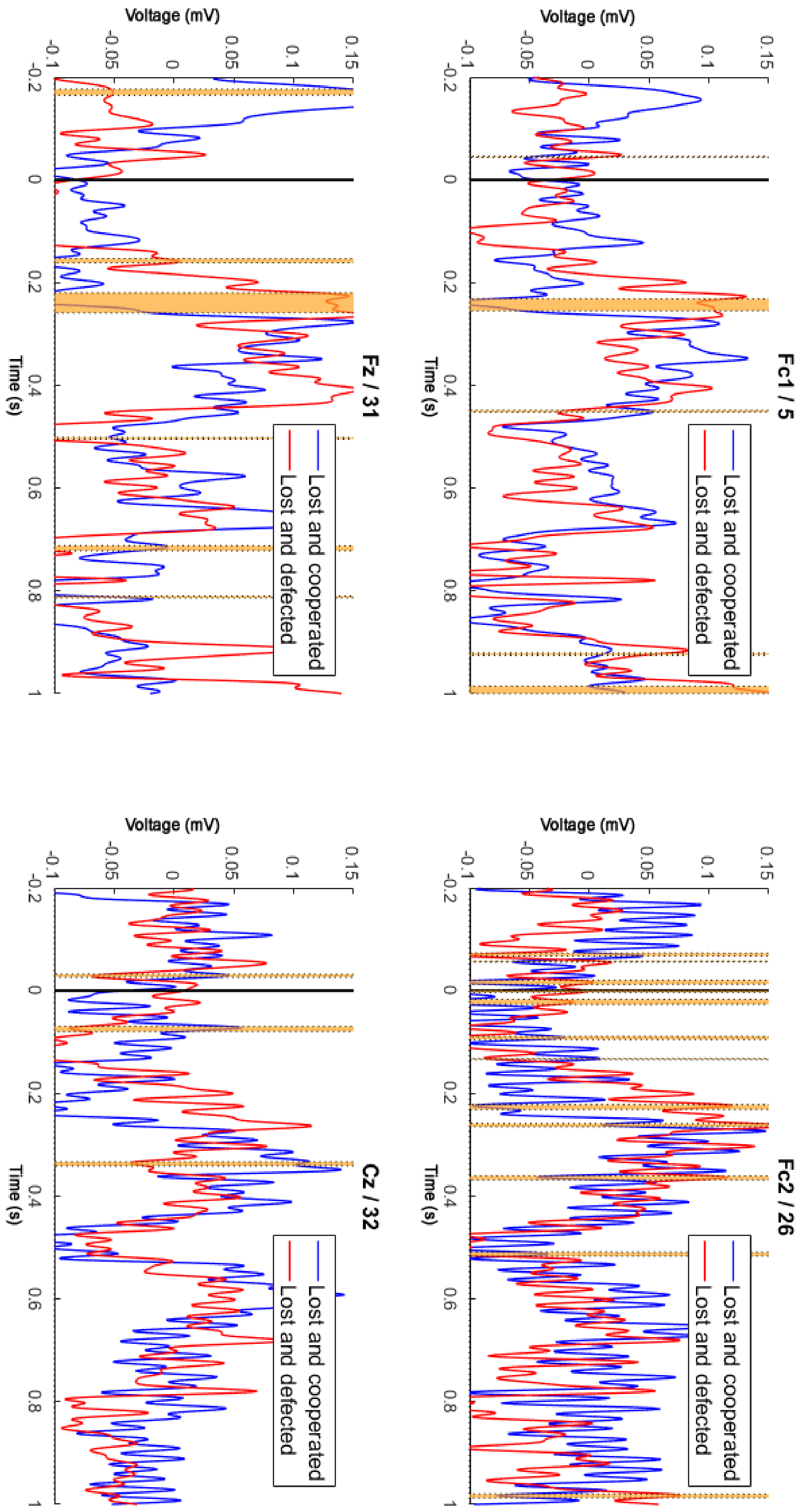


Figure H.4: Comparison of average potential for trials where players lost the current game after having cooperated or defected.