Modality Switching and Performance in a Thought and Speech Controlled Computer Game

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ABSTRACT

Providing multiple modalities to users is known to improve the overall performance of an interface. Weakness of one modality can be overcome by the strength of another one. Moreover, with respect to their abilities, users can choose between the modalities to use the one that is the best for them. In this paper we explored whether this holds for direct control of a computer game which can be played using a brain-computer interface (BCI) and an automatic speech recogniser (ASR). Participants played the games in unimodal mode (i.e. ASR-only and BCI-only) and multimodal mode where they could switch between the two modalities. The majority of the participants switched modality during the multimodal game but for the most of the time they stayed in ASR control. Therefore multimodality did not provide a significant performance improvement over unimodal control in our particular setup. We also investigated the factors which influence modality switching. We found that performance and peformance-related factors were prominently effective in modality switching.

Categories and Subject Descriptors

B.4.2 [**Input/Output Devices**]: Channels and controllers; H.5.2 [**User Interfaces**]: Input devices and strategies

General Terms

Experimentation, Human Factors, Performance

Keywords

Brain-computer interface, automatic speech recogniser, multimodal interaction, hybrid BCI, SSVEP, games

1. INTRODUCTION

Traditional human-computer interaction (HCI) modalities, mouse and keyboard, have long served as a reliable means of input. Despite their reliability, they restrict user's expressive capabilities and therefore the information transferred from the user to the computer. As a response to this problem, modern HCI uses natural human input such as speech and gestures [10]. Moreover, through brain-computer interfaces (BCIs), even brain activity can directly be provided as input to computers [18].

In real-world settings, every input recognition technology has its weaknesses. For instance, automatic speech recogniser (ASR) is affected by factors such as speaker accent and background noise [6]. Similarly, BCI is prone to artefacts due to bodily movements and electromagnetic interference. In addition, due to BCI illiteracy, it cannot be used by some people at all [15]. Thus, even after training a recogniser and/or the user, it might not be possible to achieve a perfect communication between the user and the computer. In this case, offering multiple modalities for input (i.e. multimodality) can be helpful. If multiple modalities are available for use, then people can switch to the modality they believe is most accurate and efficient for conveying particular content. In this way they can improve their own and also the system's overall accuracy [16]. Based on this fact, the first goal of this study is to verify that offering users multiple modalities in a computer game would improve their overall performance.

Besides performance, there might be other reasons for switching modality. For example in entertainment computing the primary goal of users is not to optimise the task performance. While playing a game, users (i.e. players) might still have tasks to complete but their actual purpose in playing the game is enjoyment. The feeling of enjoyment, which is often explained as flow, occurs when the player is exposed to a challenge that matches their skills [3]. In accordance with the flow phenomenon, the player may get bored using the mouse and the keyboard, which offer no challenge to them, but enjoy tackling the shortcomings of a non-traditional modality, such as BCI [14]. Therefore, in multimodal games, players might switch modality not only for improved performance, but for improved enjoyment. Knowing users' modality switching reasons is important for offering them the correct modalities for particular tasks and situations. Based on this motivation, our second goal is to investigate the factors influencing users' modality switching behaviour and preference on certain modalities in a computer game.

In this paper we will consider a realistic game (i.e. an uncontrolled experimental setup) in which players make selections (i.e. direct control) using one of the two available modalities; a steady-state visually evoked potential (SSVEP)

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based BCI and an ASR. BCI and ASR are both imperfect but natural input modalities. Moreover, they are suitable candidates for multimodal control in gaming applications, considering the assumption that the majority of the primary game controllers already occupy the players' hands. We will investigate whether users switch modality during the game and, if so, what factors influence their switching behaviour. To explore the switching factors, we will rely on interviews with the players and game logs. We will consider possible factors beyond, but not excluding, performance such as task load, usability, engagement, curiosity and fatigue.

The rest of the paper is organised as follows. In section 2, we introduce BCIs based on the SSVEP and report research related to our study. Then, in section 3, we describe our method and tools. Section 4 describes our experiment details and analysis results. In section 5 we discuss these results and in section 6 we conclude by re-stressing the important results.

2. BACKGROUND

2.1 BCIs Based on SSVEP

BCIs can infer a user's mental/emotional state or intention by interpreting brain activity. First, brain activity is acquired and quantified as a signal, which is mostly done through the use of an electroencephalograph (EEG). EEG measures electrical brain activity via electrodes in contact with the scalp. Then, the signal is processed and analysed in guidance of neuromechanisms. Neuromechanisms signify certain changes in the signal with respect to an event. The event can be a voluntary action such as moving a hand or looking at something as well as an involuntary reaction to a stimulus or an error.

SSVEP is a stimulus dependent, widely used neuromechanism. When a person attends to a visual stimulus repeating with a certain frequency, the amplitude of the signal measured from the visual brain area is enhanced at the frequency of the stimulation. This enhancement is known as the SSVEP [7]. SSVEP is frequently used for selection tasks. By presenting multiple stimuli with distinct repetition frequencies, it is possible to detect which of the stimuli a person was paying attention to. So if each of these stimuli is associated with a choice, then it is possible to detect the person's selection. The strength of the SSVEP is dependent on the stimulation properties. These include flicker frequency, size, colour and shape of the stimulus [1].

2.2 Multimodal Interaction and BCI Games

Most of the applications controlled by BCI are unimodal. This is the case mainly due to the sensitivity of brain activity measurement devices to bodily movements, even to blinking. Nevertheless there are some multimodal BCI applications developed recently [4]. Multimodal BCI games are encountered rarely in the literature but are becoming common with the advances in portable consumer BCI hardware. Finding Star [9] is such a game in which the players control the entities in the game world with emotional signals from the BCI and use the keyboard and mouse to defeat monsters and solve puzzles in the world. In the game NeuroWander [20] the players control an avatar using the keyboard and mouse while their emotional and attentional states are used in fulfilling various quests. In the Bacteria Hunt game [12] the player uses the keyboard to move an amobea at the same time trying to relax to slow down the bacteria they have to catch. In none of the aforementioned games performance or user experience factors were contrasted between multimodal and unimodal control.

Here, we find it useful to mention the concept of hybrid BCI (hBCI) which is used more regularly by the BCI community. An hBCI is defined as a system which *"can either use two different brain signals (e.g. electrical and hemodynamic signals), one brain signal (e.g. EEG) associated with two mental strategies (motor imagery and spatial visual attention), or one brain signal and another input."* [17]. Especially the last phrase of this definition (i.e. combining brain signals with other modalities) matches the multimodality phenomenon as it is employed by the HCI community. Although the definition does not impose any restrictions, so far, the motivation to build hBCIs has been limited to improve the performance of assistive technologies. This trend of practice neglects combining BCI with other modalities for non-performance purposes, such as improving user experience which is a crucial matter of concern in HCI research. The game we use in our study does not violate the definition of hBCIs but with respect to the research we conduct, we consider our game to be a multimodal system rather than an hBCI.

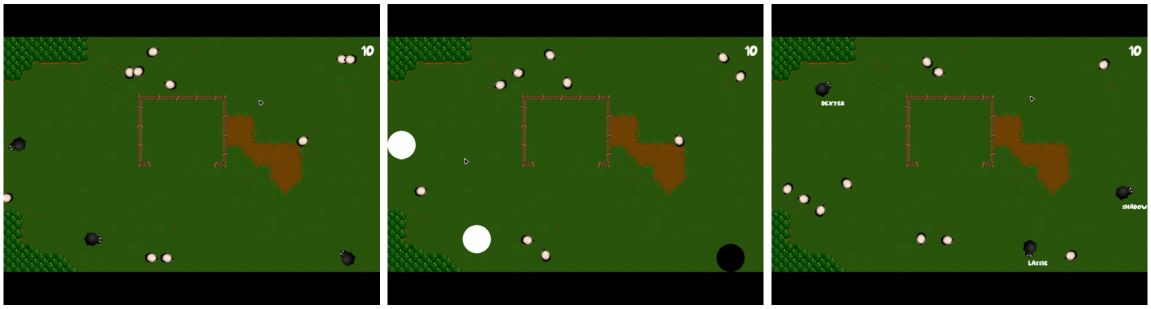
3. METHOD

3.1 Rationale

In this study we used a realistic game, thus an uncontrolled experimental platform, in order not to affect the game flow. We first let the users play unimodal games, in which only ASR or BCI is an available modality, so that they became aware of the performances of the modalities. Then we asked them to play the multimodal game where both modalities were available for use. To evaluate performance in each of the three games we analysed the objective data obtained through game logs. To investigate modality switching reasons of the players we opted for subjective analysis. This was mainly because BCI is a private input modality, preventing us from obtaining ground truth for user actions. For example when a user switches from BCI to ASR we have no objective cue to speculate on what has changed or went wrong. There are a number of subjective analysis methods such as think-aloud, retrospective think-aloud, questionnaires and interviewing [11]. We refrained from think-aloud since we did not want to force users to talk in order to sustain the natural interaction. Moreover, speaking could induce artefacts to the EEG data. We did not prefer retrospective think-aloud either because it lacks the game context which can deeply influence the user experience. Questionnaires are also not very suitable because they can not provide detailed information about specific events occurred during the game. Therefore we decided to do a semi-structured interview at the end of the experiment. We asked the users directly the reasons for switching or staying at a particular modality. Then we elaborated by some predefined potential factors which might have influenced their preferences.

3.2 The Game: Mind the Sheep!

Mind the Sheep! (see Figure 1) is a multimodal computer game where the player needs to herd a flock of sheep across a field by commanding a group of dogs. The game world



(a) (b) (c)

Figure 1: Screenshots from the game. In (a) and (b) BCI game with stimulation off and on respectively. In (c) ASR game.

contains three dogs, ten sheep, a pen and some obstacles. The aim is to pen all the sheep as quickly as possible.

To command a dog, the player positions the cursor at the point to which the dog is supposed to move. The player holds the mouse button pressed to provide the command to select the dog. Meanwhile, the game displays cues specific to the active modality (ASR or BCI). When ASR is the active modality, names appear under the dog images and the player pronounces the name of the dog they want to select. When BCI is the active modality, dog images are replaced by circles flickering at different frequencies and the player concentrates on the circle replacing the dog they want to select (so as to obtain an SSVEP). The stimulation persists and, depending on the active modality, EEG or acoustic data is accumulated as long as the mouse button is held. When the user releases the mouse button, the signal is analysed and a dog is selected based on this analysis. The selected dog immediately moves to the location where the cursor was located at the time of mouse button release. When configured, it is possible to switch between the modalities by pressing the Ctrl key on the keyboard.

3.2.1 Balancing ASR and BCI Recognition Performances

Ensuring the equivalence of the ASR and the BCI in terms of recognition performance was a concern, as this could highly affect the game experience. We did not want to artificially deteriorate the performance of modalities by introducing noise or random errors but we did try to equalise the performances by tuning game parameters. We conducted two pilot studies to standardise the recognition performances of the ASR and the BCI.

Seven non-native English speakers participated in the first pilot study in which we collected data to compare ASR performance among different sets of dog names (trios formed by candidate names Hector, Victor, Dexter, Pluto, Shadow and Lassie). To record speech, we placed the microphone behind the participant because when the microphone was in the front, the ASR performance was so high that it could not be matched by the BCI. The participants pronouced each name five times. For each name trio we computed the average recall of the recognition carried out by the ASR as described in section 3.2.3.

In the second pilot study another 7 people participated. This time we collected data to evaluate BCI performance with respect to different sets of frequencies (trios formed by candidate frequencies 6 Hz, 6.67 Hz, 7.5 Hz, 8.57 Hz, 10 Hz, 12 Hz, 15 Hz). The setup and procedure for this pilot study is described elsewhere in detail [5]. Just as in the first pilot study, for each frequency trio we computed the average recall of the recognition performed by the BCI as described in section 3.2.2.

We sorted the name trio-frequency trio pairs with respect to their similarity in average recall, which was assessed by Wilcoxon rank-sum tests (higher p-values indicated more similarity). Among the most similar name trio-frequency trio pairs, the pair with the highest average recall was selected. In this way, we decided to use Dexter, Lassie and Shadow (yielding an average recall of 83%) as dog names and 7.5 Hz, 10 Hz and 12 Hz (yielding an average recall of 84%) as flicker frequencies. This pair yielded a p-value of 0.97. We set the flicker diameter length to 3 cm. Literature also confirms that flicker frequencies between 5-12 Hz can evoke strong SSVEP and size of 3 cm can provide an optimal comfort-performance combination [1].

3.2.2 BCI Details

In our study, EEG signals were acquired and recorded by the five BioSemi Active-electrodes placed in contact with the scalp at locations PO3, O1, Oz, O2 and PO4 according to the international 10-20 system [8]. The continuous signals were digitised at a sampling rate of 512 Hz using BioSemi ActiveTwo system. No further processing was carried out in the hardware. In the game software, the digitised EEG data was re-referenced to linked-ears and processed using canonical correlation analysis (CCA) [2] including the three harmonics of each flicker frequency (i.e. fundamental frequency, second and third harmonics). The dog with the frequency that yielded the maximum correlation in CCA was selected by the game.

3.2.3 ASR Details

Speech was acquired by a microphone located to the right, behind the participants as described in section 3.2.1. Acquired acoustic data was recorded, processed and analysed using the CMU Sphinx speech recognition toolkit [19]. All the parameters were left as default except for the following: `absoluteBeamWidth=-1`, `wordInsertionProbability=1E-36`, `relativeBeamWidth=1E-80` and `languageWeight=8`. The Wall Street Journal model supplied within the Sphinx toolkit was used for the dictionary and the acoustic model. Word level unigrams representing the three dog names were used to form the language model. Then, Sphinx constructed a search graph using the acoustic model, the dictionary and the language model. The signal processing pipeline consisted of pre-emphasiser, raised cosine windower, discrete Fourier transform, mel frequency filter bank, discrete cosine transform, cepstral mean normalization and feature extraction. Decoding was performed by a frame synchronous Viterbi search on the constructed search graph using the extracted features. The dog with the name matching the result of the decoding was selected by the game. If there was no result at the end of decoding (e.g. in case of silence), no action was taken.

3.3 Interview

We prepared a semi-structured interview to be conducted at the end of the experiment to learn about users' reasons to switch or stay at a particular modality. The interviews were conducted by the first author of the paper. He read the questions one by one, as they were written on the paper in front of him. The interview was videotaped for post-experiment analysis. The interview began with the question "Did you switch modality during the last game?" and followed by "Why?" or "Why not?" depending on user's answer to the first question. This way, without cueing the user, we identified the factors affecting their preference. Then we asked specifically about possible factors which might have influenced their preference: "Was [factor] a reason for switching from or staying at one modality?" The factors were usability, engagement, task load, performance, tiredness and curiosity. If the answer was just a Yes/No, then we asked "Can you explain?". Finally we repeated our first question as: "Are there any other reasons for switching from or staying at one modality?" in order to extract possible additional reasons that might have been triggered during the interview.

4. EXPERIMENT

4.1 Participants

Twenty people (3 female) participated in the experiment. They had an average age of 24.9 ($\sigma = 2.87$), ranging from 19 to 29 years, and normal or corrected vision. None of them were native English speakers. Eight of them had previous experience with BCIs and fourteen of them with ASRs. Six of them indicated that they played games more than five hours per week. Informed consent was obtained from all participants and they were paid according to the regulations of our institution.

4.2 Procedure

Participants sat on a comfortable chair approximately 60 cm away from a 20″ screen with a resolution of 1280 × 960. They played Mind the Sheep! once with BCI and once with ASR in counterbalanced order to diminish the effect of familiarity with the game. Then they played the multimodal game. They played each game until all the sheep were penned or the play time reached 10 minutes. Games ran on full screen. In the ASR game, BCI control was not available and brain signals were not analysed while in the BCI game, ASR was not available and speech was not recognised. During neither the ASR nor the BCI game could the participants switch between modalities. During the multimodal game both ASR and BCI controls were available, one active at a time. The starting modality was selected randomly. The players could switch between the modalities at any time by pressing the Ctrl key. During all games, each key press and mouse click was time-stamped and logged. The game world layout was different in each game but comparable in difficulty.

4.3 Analysis

We grouped the participants according to their modality switching motivations based on the interview answers. We defined two groups: active switchers and non-switchers. Non-switchers were those who did not switch modality at all and those who switched only at the beginning of the game to decide on which modality to use. These people continuously used a single modality until the end of the game and penned the sheep using one modality. The rest of the participants were active switchers. They reported switching modality during the game after some errors or knowing that certain selections were easier using a particular modality.

To investigate whether using multiple modalities improved performance, for each of the three games played by active switchers, we calculated the number of selections (i.e. number of times the mouse button was released) and game duration as indicators of performance. We expect that the performance of active switchers in the multimodal game would be higher than that in both unimodal games. We calculated the same statistics for the multimodal game played by non-switchers as well as for the preferred and non-preferred unimodal games. For example if a non-switcher stayed at the BCI modality during the multimodal game, then their preferred unimodal game would be the one that they had played using the BCI and their non-preferred unimodal game would be the one that they had played using the ASR. We expect that in the multimodal game non-switchers would achieve a performance better than that in their non-preferred unimodal game and comparable to that in their preferred unimodal game.

To study the modality switching motivations of the participants, we extracted from the interviews the factors for switching or staying at a modality. We combined these with the pre-determined factors which we explicitly asked during the interview. We computed the total number of participants reporting each factor.

Although we computed and report the means in analysis results, we opted for non-parametric statistical testing for assessing the significance of all differences since we neither can assume nor could prove normally distributed samples. Thus, the significance of differences mentioned throughout the paper were assessed by the Wilcoxon signed-rank test ($p < 0.05$). Moreover, the Bonferroni correction was applied during the analyses reported in subsection 4.4 ($p < 0.017$). Unless otherwise stated, reader should assume non-significant difference.

4.4 Results

4.4.1 *Performance Analysis*

Of the 20 participants, 6 were identified as non-switchers and 14 as active switchers. The box plots in Figure 2 demonstrate scores belonging to the two performance indicators for the unimodal (i.e. ASR and BCI) and multimodal games played by active switchers. The number of selections were not different in BCI ($\mu = 72.64$, $\sigma = 35.48$), ASR ($\mu = 75.00$, $\sigma = 36.94$) and multimodal ($\mu = 73.93$, $\sigma = 46.61$)

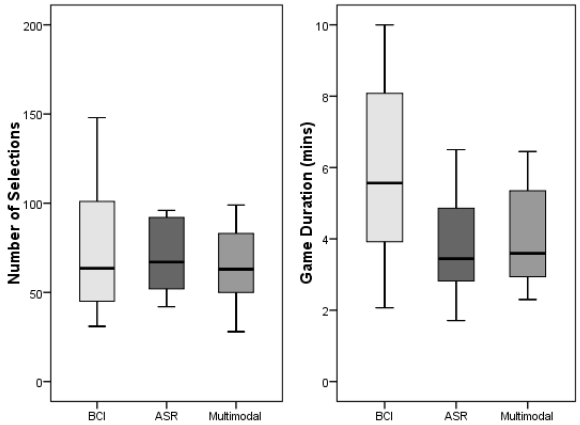


Figure 2: Performance indicators for the BCI, ASR and multimodal games played by active switchers: Average number of selections (left) and average game duration (right).

games. The duration (in minutes) was longer for the BCI game ($\mu = 5.92$, $\sigma = 2.45$) compared to ASR ($\mu = 4.11$, $\sigma = 2.11$) and multimodal ($\mu = 4.60$, $\sigma = 2.54$) games. The difference between the BCI game duration and ASR game duration was significant.

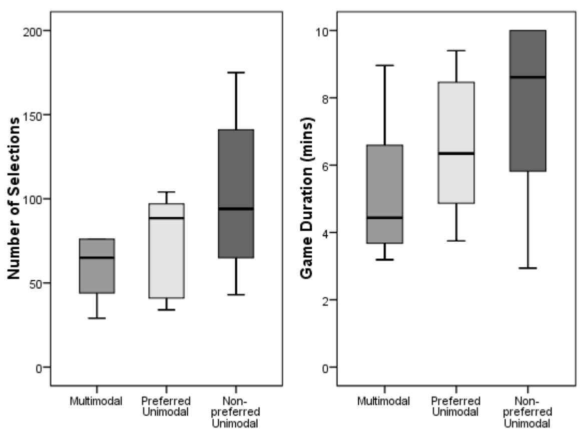


Figure 3: Performance indicators for the multimodal, preferred unimodal and non-preferred unimodal games played by non-switchers: Average number of selections (left) and average game duration (right).

Figure 3 illustrates the performance related scores across non-switchers for the multimodal game they played as well as for the their preferred and non-preferred unimodal games. During the multimodal game 4 people stayed at BCI control while 2 people preferred ASR control. The number of selections during the multimodal game ($\mu = 72.00$, $\sigma = 43.31$) was less than that during the preferred unimodal game ($\mu = 75.50$, $\sigma = 30.16$) which in turn was less than that during the non-preferred unimodal game ($\mu = 102.00$, $\sigma = 48.74$). The same relationship can be observed for the duration (in minutes) of multimodal ($\mu = 5.21$, $\sigma = 2.17$), preferred unimodal ($\mu = 6.53$, $\sigma = 2.18$) and non-preferred unimodal ($\mu = 7.66$, $\sigma = 2.88$) games. None of the differences were significant.

4.4.2 *Modality Switching Analysis*

Figure 4 shows the number of people reporting a factor as affecting their modality switching or preference. No factors different than those we had set before the experiment were identified during the interviews. Twenty people indicated that performance was a factor affecting their choices. This factor was followed by usability (14 people), curiosity (12), engagement (7), task load (6) and fatigue (5).

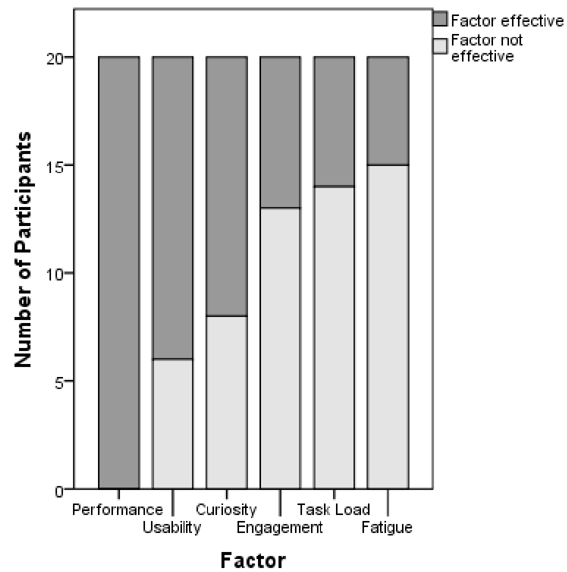


Figure 4: Per factor, number of participants reporting whether it was effective or not in modality switching or preference.

5. DISCUSSION

5.1 Performance Results

Log analysis results did not confirm our expectation that active switchers' performance in the multimodal game would be higher than that in both unimodal games. We found that the number of selections during active switchers' multimodal and unimodal games were comparable. Also the duration of the multimodal game was not significantly different than that of either unimodal game although the unimodal BCI game lasted significantly longer than the unimodal ASR game.

We performed some additional analyses to explain our findings. Firstly, we were interested in why the unimodal BCI game lasted significantly longer than the unimodal ASR game although the number of selections were not different. We thought this could be related to the difference in average selection times between the two modalities. Figure 5(a) shows the average selection duration in the unimodal games. Indeed, during the unimodal BCI game selections lasted significantly longer than the unimodal ASR game. In this case, while making a selection during the unimodal BCI game, the game state would change more than it would in the unimodal ASR game. This might necessitate recreating a strategy after some selections in the unimodal BCI game thus increase the game completion time.

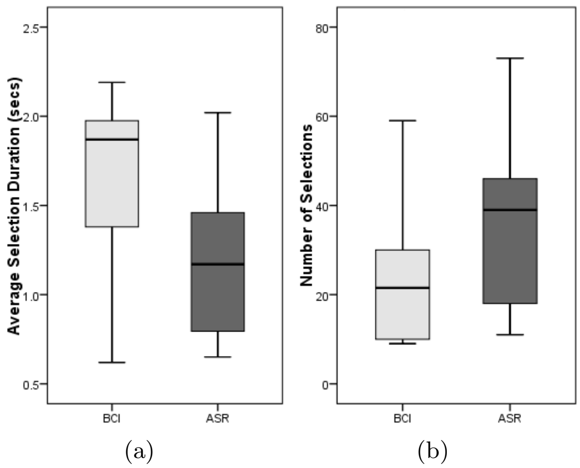


Figure 5: (a) Average selection duration during unimodal games, (b) Number of selections made by active switchers per modality during the multimodal game.

Secondly, we were interested in why the unimodal ASR and multimodal games lasted in very similar times. We hypothesised that during the multimodal game players used ASR more frequently than BCI. To investigate this we extracted the number of selections per modality during the multimodal game. As Figure 5(b) displays, during the multimodal game more number of selections were performed using ASR than that using BCI, although the difference is not significant. Nevertheless, interview results provided some clues supporting our hypothesis. Of the 14 active switchers, 7 indicated that they could not command the dog "Dexter" so switched to BCI when they wanted to control this particular dog. If we assume that they used BCI to control one dog and ASR to control the remaining two, then they would be in ASR mode more frequently than the BCI mode. This can explain why the game durations were comparable in the unimodal ASR and multimodal games.

For non-switchers, our expectations were partly verified by log analysis results. The multimodal game required comparable number of selections and time to complete as with the preferred unimodal game. Also as expected, the multimodal game lasted shorter than the non-preferred unimodal game and took less number of selections. However the differences were not significant probably due to the small sample size. The latter finding might be due to the learning effect as the multimodal game was always played after the unimodal games. It is possible that players gained experience with their preferred modality during the corresponding unimodal game and performed better during the multimodal game using their preferred modality exclusively.

5.2 Modality Switching Results

The participants unanimously indicated that performance was *the* factor in their modality preference. They changed modality when their commands were not understood by the game or they did not change at all knowing that otherwise their commands would not be understood. Log analysis results which we provided in the previous subsection confirmed that non-switchers were able to achieve a better performance in multimodal game but active switchers could improve their performance in the multimodal game only in comparison to the BCI game. Fourteen people reported usability as an influencing factor, which is a concept tightly coupled with the accuracy of an interface [13]. Twelve people (out of 14 active switchers, as this factor only applies to them) indicated that curiosity was a reason to switch modality. However they explained that the curiosity originated when their commands were interpreted incorrectly so that they wanted to see whether the other modality would recognise the command correctly. So this item was tightly coupled to performance as well. Engagement was not a major factor in modality choice. The shortcomings of BCI did not seem to introduce a challenge and improve engagement in this particular game context. Task load and fatigue were also not reported as major factors. Participants were not disturbed by the stimulation while using BCI and they were not tired of putting in effort to use the modalities.

6. CONCLUSIONS

In this paper, we investigated whether providing multiple modalities to players would improve their direct control performance. In an experiment we let 20 participants play two unimodal games, once using a BCI and once using an ASR. Then they played a multimodal game where they could switch between BCI and ASR control whenever they wanted. From the game logs we extracted the number of selections made and game durations for the unimodal and multimodal games as objective indicators of performance. The analysis results showed that 14 participants actively switched modality during the multimodal game while 6 preferred to use a single modality. Active switchers made comparable amount of selections in unimodal and multimodal games. Though non-significantly, their multimodal games lasted shorter than their unimodal BCI game. We found that this difference occurred because during the multimodal game active switchers used ASR control more frequently than BCI control. This suggests that active switchers tended to play using ASR but switched to BCI when ASR did not respond correctly in some particular situations. Non-switchers made comparable number of selections during the unimodal and multimodal games and also finished each game in similar amount of time. Consequently, we cannot conclude that multimodality improved direct control performance in our experimental conditions. We suggest that for direct control BCI is not a preferred alternative to more reliable modalities, such as ASR.

We also investigated what factors, including but not limited to performance, affect players' modality switching or preferences. In a post-hoc interview with participants, we asked them about the reasons to switch or prefer a particular modality. They unanimously indicated that improving the performance was their utmost aim. We also found that usability, a concept highly correlated to the performance of an interface, was a major factor. Curiosity, about the performance of the other modality, was a factor in cases when a modality did not work as expected. The other factors namely engagement, task load and fatigue were not reported as major modality choice factors. It appeared to be that even the non-performance related factors were influenced by the accuracy of the interface. This suggests that before evaluating the non-performance related aspects of an imperfect interface used for direct control of an application, a high accuracy should be guaranteed and that this holds for entertainment applications as well.

Our findings are not necessarily against using BCIs in games. Instead of direct control which leads players to strive for the best performance, BCIs can be used to control less vital dynamics of the game. For example, through passive BCIs [21] a player's state of relaxedness can continuously be monitored and used as an auxiliary controller which tunes the look of a game or other game parameters. So passive BCIs might relax the requirements on performance and timeliness of BCI recognition. We also argue that our findings do not oppose using SSVEP-based BCIs for direct control in games. The game used in our study relied on an SSVEP-based BCI to make selections, which is the most common practice with these BCIs. For example the SSVEP, obtained using a single stimulus (rather than 3 stimuli as we used in our game), can be used to determine a player's concentration level and mapped to actions or a decision mechanism in the game. This might assign a more intuitive function to an SSVEP-based BCI and make it easier for the player to use.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] J. Bieger and G. G. Molina. Light stimulation properties to influence brain activity: A brain-computer interface application. Technical Report TN-2010-00315, Philips Research, Eindhoven, The Netherlands, 2010.

[2] G. Bin, X. Gao, Z. Yan, B. Hong, and S. Gao. An online multi-channel SSVEP-based brain-computer interface using a canonical correlation analysis method. *Journal of Neural Engineering*, 6(4):046002, 2009.

[3] M. Csikszentmihalyi, S. Abuhamdeh, and J. Nakamura. Flow. In *Handbook of Competence and Motivation*, pages 598–608. The Guilford Press, New York, NY, USA, 2005.

[4] H. Gürkök and A. Nijholt. Brain-computer interfaces for multimodal interaction: a survey and principles. *International Journal of Human-Computer Interaction*, 2011. To appear.

[5] G. Hakvoort, B. Reuderink, and M. Obbink. Comparison of PSDA and CCA detection methods in a SSVEP-based BCI-system. Technical Report TR-CTIT-11-03, Centre for Telematics and Information Technology, University of Twente, Enschede, The Netherlands, 2011.

[6] J.-P. Haton. Automatic speech recognition: A review. In *Enterprise Information Systems V*, pages 6–11. Springer, Dordrecht, The Netherlands, 2005.

[7] C. S. Herrmann. Human EEG responses to 1–100 Hz flicker: resonance phenomena in visual cortex and their potential correlation to cognitive phenomena. *Experimental Brain Research*, 137(3–4):346–353, 2001.

[8] H. H. Jasper. Report of the committee on methods of clinical examination in electroencephalography: 1957. *Electroencephalography and Clinical Neurophysiology*, 10(2):370–375, 1958.

[9] M. Ko, K. Bae, G. Oh, and T. Ryu. A study on new gameplay based on brain-computer interface. In *Proceedings of the DiGRA 2009*. Brunel University, London, UK, 2009.

[10] P. Kortum. *HCI Beyond the GUI*. Morgan Kaufmann, San Francisco, CA, USA, 2008.

[11] R. L. Mandryk, K. M. Inkpen, and T. W. Calvert. Using psychophysiological techniques to measure user experience with entertainment technologies. *Behaviour & Information Technology*, 25(2):141–158, 2006.

[12] C. Mühl, H. Gürkök, D. Plass-Oude Bos, M. E. Thurlings, L. Scherffig, M. Duvinage, A. A. Elbakyan, S. Kang, M. Poel, and D. Heylen. Bacteria Hunt: Evaluating multi-paradigm BCI interaction. *Journal on Multimodal User Interfaces*, 4(1):11–25, 2010.

[13] J. Nielsen. *Usability Engineering*. Morgan Kaufmann, San Francisco, CA, USA, 1993.

[14] A. Nijholt, B. Reuderink, and D. Oude Bos. Turning shortcomings into challenges: Brain-computer interfaces for games. In *Intelligent Technologies for Interactive Entertainment*, pages 153–168. Springer-Verlag, Berlin/Heidelberg, Germany, 2009.

[15] A. Nijholt, D. Tan, G. Pfurtscheller, C. Brunner, J. del R. Millán, B. Allison, B. Graimann, F. Popescu, B. Blankertz, and K.-R. Müller. Brain-computer interfacing for intelligent systems. *IEEE Intelligent Systems*, 23:72–79, 2008.

[16] S. Oviatt. Taming recognition errors with a multimodal interface. *Communications of the ACM*, 43:45–51, 2000.

[17] G. Pfurtscheller, B. Z. Allison, C. Brunner, G. Bauernfeind, T. Solis-Escalante, R. Scherer, T. O. Zander, G. Mueller-Putz, C. Neuper, and N. Birbaumer. The hybrid BCI. *Frontiers in Neuroprosthetics*, 4:30, 2010.

[18] D. Tan and A. Nijholt, editors. *Brain-Computer Interfaces: Applying our Minds to Human-Computer Interaction*. Springer-Verlag, London, UK, 2010.

[19] W. Walker, P. Lamere, P. Kwok, B. Raj, R. Singh, E. Gouvea, P. Wolf, and J. Woelfel. Sphinx-4: A flexible open source framework for speech recognition. Technical Report SMLI TR-2004-139, Sun Microsystems Inc., Menlo Park, CA, USA, 2004.

[20] M.-S. Yoh, J. Kwon, and S. Kim. NeuroWander: a BCI game in the form of interactive fairy tale. In *Proceedings of the Ubicomp '10*, pages 389–390, New York, NY, USA, 2010. ACM.

[21] T. O. Zander and C. Kothe. Towards passive brain-computer interfaces: applying brain-computer interface technology to human-machine systems in general. *Journal of Neural Engineering*, 8(2):025005, 2011.