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Supervisor: Vincent van de Ven
Group: 23 (In the Flow)
BA Psychology, Maastricht University
Faculty of Psychology and Neuroscience, the Netherlands
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Being in the Flow - An Assessment of Memory Improvement and Changes in Heart Rate Variability due to Flow State

Düster Julie, Ferbert Samuel, Gyulavari Anna, Kästingschäfer Marius, Lehto Annaliis, Schulz Corinna, Weber-Schäfer Luca, Stockert Laurids, Windfuhr Fabian

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Contents

Abstract

The positive psychology concept flow is defined as the rewarding experience of being fully immersed in a task. In order to reach flow state, a balance of challenge and skills, explicit feedback, indistinct sense of time, positive affect and intrinsic motivation are crucial. This study investigated physiological correlates of flow, as well as the effect of flow on memory performance. Two different tasks were used: a smartphone game called Piano Tiles, and a modified Orientation Discrimination Task (ODT). It was hypothesized (1) that flow and heart rate variability (HRV) are negatively associated and (2) that flow and memory recognition rates in the modified ODT are positively associated. In order to investigate these hypotheses, participants completed three sessions: ODT training, ODT while recording HRV, and Piano Tiles while recording HRV. It was found that both tasks were flow-inducing. Moreover, higher subjective flow ratings were associated with increases in HRV, contradicting previous findings. Furthermore, contrary to expectations, overall memory recognition was highest when items were presented in a less-flow state. This study may have important implications for developers of educational games, who can use these insights, in order to improve memory performance and thereby also learning performance.

Keywords: *flow, memory, heart rate variability (HRV)*

1 Introduction

Flow is a deeply enjoyable experience characterized by full immersion into a task (Csikszentmihalyi, 1975a). It was coined by Csikszentmihalyi in 1975, who observed painters getting fully absorbed into their work, while completely disregarding their surroundings. Csikszentmihalyi noticed that once a painting was finished, it became uninteresting to its creator. This highlights one of the central characteristics of flow: People seek flow for itself because it is intrinsically rewarding (Csikszentmihalyi, 1975b).

Flow can assume different intensities, ranging from simple to deep flow experiences (Privette, 1983). A number of components thought to be characteristic of flow have been established in order to distinguish between simple, deep, and non-flow experiences. These components include the balance of challenge and skills, explicit feedback, an indistinct sense of time, positive affect, high arousal levels, and intrinsic motivation (Ellis, Voelkl, & Morris, 1994; Csikszentmihalyi, 1975a; Rheinberg & Engeser, 2018).

Recently, physiological arousal measurements have received attention as possible correlates of flow (Peifer, Schulz, Schächinger, Baumann, & Antoni, 2014). One of these physiological arousal measurements is heart rate variability (HRV). It is calculated by analyzing the variability of intervals between heartbeats (Allen, Chambers, & Towers, 2007). A high HRV means that the time periods between the heartbeats differ significantly from each other, whereas a low HRV means that the heart beats occur at a constant pace. A study by Keller, Bless, Bloman, and Kleinböhl (2011) looked at the relation between HRV and flow, by varying the degree to which skills and demands are matched. A high congruity, which refers to a good match between skills and demands, was found to be an important precursor of flow. The researchers showed that HRV may be decreased by two factors: increased mental workload and a deep involvement in the task. The combination of those two factors in the high congruity and thus high flow condition led to significantly decreased HRV compared to low mental workload condition. Moreover, a great difference between the congruent condition and mental overload condition implyed that the increased involvement in the task during congruent condition may be able to account for the additional decrease in HRV.

Another possible candidate for measuring flow is electrodermal activity, also known as skin conductance response (SCR). SCR measures changes in conductivity as a result of changes in sweat secretion. In a study by Nacke and Lindley (2008), participants were instructed to play a first-person shooter in three different conditions, boredom, immersion and flow, while SCR was measured. The researchers found significant differences between the three conditions and recorded the highest levels of SCR in the flow condition. These findings support the hypothesis that changes in SCR may be a consequence of changes in the experience of flow.

A new line of research has emerged, which constitutes rather unchartered territory. It investigates the relationship between memory and flow. It is well established, that flow induces a sense of deep enjoyment and therefore is intrinsically rewarding (Jackson, 1996). It has been suggested that intrinsic reward can improve episodic memory. An increase in the release of the neurotransmitter dopamine, which is linked to intrinsic reward, can enhance hippocampal plasticity during memory encoding or consolidation, which thereby can improve learning (Frey & Morris, 1998; Lisman & Grace, 2005; Lisman, Grace, & Duzel, 2011; Redondo & Morris, 2011). Therefore, it is reasonable to assume that the intrinsic enjoyment, which is experiened while being in the flow state, could act as a rewarding signal. This rewarding signal could then increase the memory of experiences encountered during the flow state. Thus, being in the flow could have a positive effect on memory.

Investigating the effect of flow on memory is practically relevant for designing educational games. Digital educational games refer to anything that combines video games and education (Moreno-Ger, Burgos, Martínez-Ortiz, Sierra, & Fernández-Manjón, 2008). The relevance of using a well-designed game to induce flow is illustrated in a study by Kiili (2005), who argues that it is important to consider flow in the context of educational games because it enhances the user experience and thus increases learning. He proposed a model for educational gaming, in which flow plays an essential role. According to this model, the key features of a flow-facilitating game are immediate feedback, clear goals, and a balance between the demand of the task and the user's skills. Therefore, understanding the effects of flow on memory in instructional systems possibly contributes to game development for educational application.

The current study investigated physiological correlates of flow, as well as the link between flow and memory performance. In order to achieve this, the study used two tasks, a smartphone game (Piano Tiles for Android and iOS, developed by Cheetah Games), and a visual orientation discrimination task (ODT). A questionnaire was used to assess the qualitative experience of flow. It was hypothesized that the game as well as the ODT are flow inducing. During both tasks, the participants were connected to a device that measured their heart rate variability (HRV) as well as their skin conductance response (SCR). It was hypothesized that as flow increases, HRV decreases and SCR increases. In the smartphone game, flow was assessed by looking at the first and the second half of the game independently. It was hypothesized that the second half of the game would be more flow inducing than the first half of the game, due to increasing task difficulty. In the ODT, flow was measured by looking at the first and the second half of flow states. It was hypothesized that the second half of flow states would be more flow inducing than the first half. Furthermore a memory recognition task was included in the ODT, which was used to investigate the link between memory and flow. It was hypothesized that pictures that were shown during the second half of flow states of consecutive correct trials within the ODT would be memorized better than pictures shown in the first half.

2 Materials and Methods

2.1 Participants

Participants. The sample in the study consisted of 26 participants (21 female, 5 male) between the age of 20 and 28. All participants gave written informed consent and were debriefed after the completion of the study. Participants were acquired through the Maastricht University SONA platform, where they were able to apply for the study in response to a previously distributed advertisement. In agreement with the given guidelines, the sample of 26 participants was limited to second-year psychology bachelor students from Maastricht University. Participants were informed about the tasks they had to perform, on the involved psychophysical arousal measurements and the duration of their participation. Participants were compensated for their participation with SONA participation points. Out of the 26 participants, one participant was excluded from statistical analysis completely, due to technical difficulties. The data of 25 (21 female, 4 male) participants were used in the analysis of the questionnaires and the memory performance analysis. The data of 22 (19 female, 3 male) participants were used for the heart rate variability (HRV) analysis. The SCR data was not analyzed in the current manuscript due to issues with data quality and analysis.

2.2 Materials

Piano Tiles Task. Piano Tiles is a game that can be played on a smart-phone. During the game, black bars appear at the top of the screen and quickly descend towards the bottom of the screen (Figure 1). The participant's task was to tap on the black bars before they reached the bottom of the screen. The bars represent the melody of a song, and by tapping on them, the sound of a melody is created. The length of the black bars indicates how long a bar has to be pressed. The game continued until the player made an error. The game was over, either when the participant missed a black bar before it touched the bottom of the screen, or if the participant tapped on a white tile. All participants played on the same smartphone and the same song was used for every participant. All participants had two minutes to get acquainted with the game. Afterwards, participants were given 20 minutes to play the game multiple times. The duration of each game was dependent on the performance level of the participant.

This particular game was used due to its potential flow inducing properties. For instance, the game was easy enough to be learned quickly, but at the same time, stayed demanding enough for the participant, due to the increasing task difficulty while playing the game. Therefore, the game provided an adequate balance between skills and demands. Additionally, the melody created while playing the game could be interpreted as continuous feedback on the participant's performance. Lastly, the fact that the aim of the game was to entertain could be seen as a motivation factor that enables flow.

Visual Orientation Discrimination Task (ODT). The ODT is a computer-administered visual orientation discrimination task implemented in Psychopy (Peirce, 2007). The modified version used in this study consisted of 4 runs of the ODT. Each of the runs consisted of 60 to 100

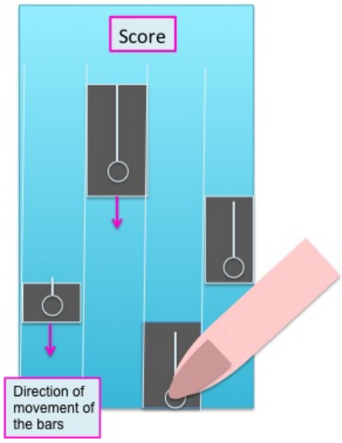

Figure 1: ***Piano Tiles Setup****.This picture represents the setup of the Piano Tiles smartphone game. The black bars represent the tiles that the participant is required to press while they are moving down towards the bottom of the smartphone screen. Tapping the spaces in between the black tiles means an error and ends the game. Furthermore, the length of the black tiles indicate how long a tile has to be pressed. At the top of the screen the score is shown, which is currently zero, as the game has not started yet.*

discrimination trials. The participants were asked to fixate on a cross in the middle of a computer screen. Periodically, a Gabor patch (test stimulus), corresponding to gratings of different orientations, appeared in the center of the computer screen. This test stimulus was rotated either clockwise or counterclockwise, relative to a reference orientation that the participants had not previously seen. Participants were required to discriminate the test stimulus against the unknown reference orientation. If the participants judged the test stimulus to be rotated clockwise relative to the reference, the subject pressed the right arrow on the computer keyboard. When the participants judged the test stimuli to be rotated counterclockwise to the reference they pressed the left arrow of the computer keyboard (Figure 2). Each trial started with a warning cue (fixation cross appeared and was displayed for 500 msec), after which the target stimulus was shown for 300 msec. Participants had 3 seconds to respond after target stimulus onset and received feedback about their response. Each time a correct judgement was made about the orientation, a green light was shown in the middle of the center. an incorrect judgement was made about the orientation, a red light appeared in the centre (Figure 3). Each time an incorrect judgement was made about the orientation, a red light appeared in the centre The length of the ODT depended on the performance of the participant. The ODT used in this study included a maximum of 14 reversals. A reversal occurred each time the participant discriminated the grating incorrectly. This led to the conclusion that the better a participant was, the fewer reversals he or she had, and the longer he or she performed the ODT. The maximum number of trials amounted to 100, independent of whether the maximum number of reversals was reached during the ODT. If a participant reached the maximum number of reversals before reaching the maximum number of 100 trials, the ODT was terminated. The ODT operated according to a staircase model (Figure 4). This staircase model facilitated the experience of flow, because it adapts the difficulty level of the ODT to the participant's current performance level. The difficulty level of discriminating the rotation of the test stimulus increased after 4 consecutive correct responses, which meant that the orientation difference decreased by one unit and that the task became more difficult. Making a single error resulted in a one unit increase in orientation difference, meaning that the task became easier. The achieved orientation difference at the end of one run indicated the skill level of a participant. The staircase model therefore created a perfect match between skills and demands, which is required for the experience of flow. Furthermore, the program gave immediate feedback about the correctness of the participant's judgements, thereby giving the participant a hint about the reference grating.

The ODT was preceded by a practice session to familiarize the participants with the ODT. The practice task differed from the actual ODT in a way that the test stimuli were presented in isolation, surrounded only by a gray background. During the ODT, pictures of landscapes surrounded the appearing test stimuli (Figure 5). The participants were asked not to attend to the pictures and to focus only on the gratings.

Memory recognition task. In this task, the participants were required to indicate which of the two pictures shown to them was previously presented during the ODT (Figure 6). The correctness of the answers and the reaction time were assessed and compared to the hit rate pattern in the ODT.

Questionnaires. Participants retrospectively rated their experience of flow during the performance of either the ODT or the Piano Tiles game on two modified flow scales, ranging from 0 “I do not agree at all ” to 4 “I agree extremely”. The ODT questionnaire (Table 1, left) consisted of 15 carefully selected statements that covered three different aspects of the subjective experience of flow: challenge, competence and flow (IJsselsteijn, De Kort, & Poels, 2008). The Piano Tiles questionnaire (Table 1, right) consisted of 5 carefully selected questions, which were asked for both the beginning of the game, as well as for the end of the game. The shortness of the questionnaire was due to the high number of games within the 20 minutes playtime, and the division of the items into those concerning the beginning of the game and those concerning the end of the game.

Physiological measures. During the runs of the ODT and the runs of the Piano Tiles, the participants’ skin conductance response (SCR) and their heart rate variability (HRV) were measured and analysed with the Biopac device (Figure 7). In order to measure the HRV, one electrode was placed on the participant’s left index finger. In order to measure the SCR, two electrodes were placed on the middle and the ring finger of the participant’s left hand.

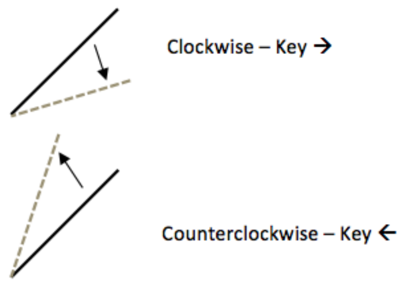

Figure 2: ***Clockwise and Counterclockwise***. *This figure represents the instructions given to the participant. In the case that the participant judged the test stimulus to be rotated clockwise to the reference stimulus, the participant was required to press the right key. In the case that the participant judged the test stimulus to be rotated counterclockwise to the reference stimulus, the participant was required to press the left key.*

Questionnaire for ODT
1. I felt skillful
2. I was fully occupied with the game
3. I felt competent
4. I thought it was hard
5. I forgot everything around me
6. I was good at it
7. I felt successful
8. I was fast at reaching the game’s targets
9. I felt pressured
10. I lost track of time
11. I felt challenged
12. I was deeply concentrated in the game
13. I lost connection with the outside world
14. I felt time pressure
15. I had to put a lot of effort into it

Questionnaire for Piano Tiles
Beginning of the game
1. I was fully occupied with the game
2. I forgot everything around me
3. I lost track of time
4. I was deeply concentrated in the game
5. I lost connection with the outside world
End of the game
1. I was fully occupied with the game
2. I forgot everything around me
3. I lost track of time
4. I was deeply concentrated in the game
5. I lost connection with the outside world

Table 1: ***Flow questionnaire items***. *Shortened versions of the Likert-scale used by IJsselsteijn et al. (2008) in their study. Some minor adaptations were made to adjust the questions to our necessities. The questionnaires were administered after each run in the ODT and after longer Piano Tiles game (for details, see 2.3 Procedure)*

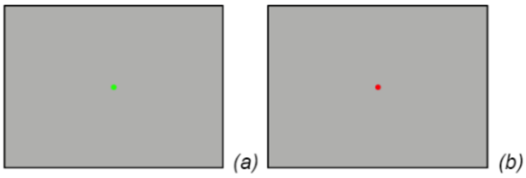

Figure 3: ***Feedback***. *These figures represent the feedback that was given to the participants. The green dot (a) appeared in the case of a correct grating jugement and the red dot (b) appeared in the case of a wrong grating judgement.*

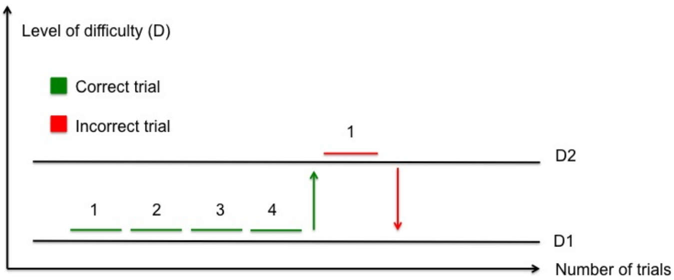

Figure 4: ***Staircase Model***. *The figure represents a schematic overview of the staircase used in the ODT. A participant was required to make four correct responses (1, 2, 3, 4) in order for the task to increase in difficulty by one level (D1 to D2). As soon as the participant made an error, the task decreased in difficulty by one level (D2 to D1). This setup enabled a perfect match between the participants' skills and the demands of the task.*

2.3 Procedure

Participants were required to come to the laboratory for a total of three sessions on consecutive days. In the first session, the participants were first given instructions on the experiment and signed the informed consent. Then they were required to perform the practice session of the ODT, consisting of 4 runs. No arousal measurements were recorded and the participants were not required to fill out a questionnaire, nor to perform the memory recognition task.

At the beginning of the second session, the participants were again given instructions and they were connected to the Biopac device in order to record their HRV and SCR. Then, the participants performed the ODT, consisting of 4 runs. The participants' HRV and SCR were measured

Figure 5: ***Test stimulus ODT***. *The picture is representative of a test stimulus used in the ODT. The grey circle with the striped pattern in the middle of the picture is the Gabor patch, whose orientation the participants were required to judge. The surrounding street image is one of the images that might be presented later on in the memory recognition task. The participant was instructed not to pay attention to the surrounding picture and to focus only on the Gabor patch.*

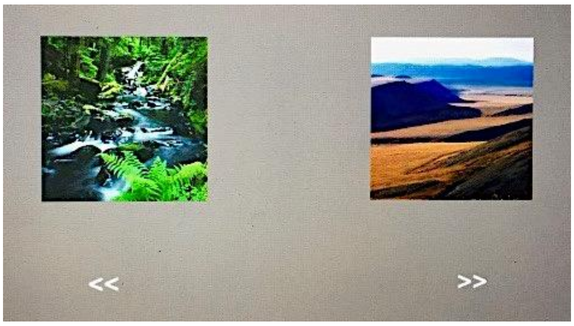

Figure 6: ***Memory Recognition Task.*** *This picture represents the forced choice method in the memory recognition task. The participant was required to choose between 2 pictures presented to him. One corresponded to a picture previously seen during the ODT and the other corresponding to a new picture. The participant was instructed to choose the picture previously shown.*

Figure 7: ***Biopac Device****. Biopac is a device to measure and to analyse physiological responses such as SCR and HRV. The machine needs to be connected to a computer with AcqKnowledge software to record the data (Biopac. http://www.biopac.com).*

during the whole ODT. After each run, the participants were required to first perform the memory recognition task and then asked to complete the modified ODT flow questionnaire, which retrospectively assessed their experience of flow during the ODT.

After receiving instructions at the start of the third session of the experiment, the participants were again connected to the Biopac device. Then, the participants practiced the smartphone game Piano Tiles for two minutes. Afterwards, they were required to play the game for another 20 minutes. Participants' SCR, as well as their HRV, were measured during each game. After a game that lasted longer than 30 seconds, the Piano Tiles flow questionnaire was filled out by the participants, which retrospectively assessed their experience of flow during the playtime.

Due to the properties of the learning process, the first and second session always followed each other. Furthermore, Session 1-2 and session 3 were not counterbalanced, to avoid carryover effects in participants. The experience of flow was hypothesized to be larger in the game than in the ODT task, and counterbalancing would, therefore, have changed the experience of flow in an ODT task following the game task.

3 Analysis

The analysis follows the order of our hypotheses, thereby first analyzing the questionnaires, followed by the physiological arousal measurement and ending with the memory recognition test. The three hypotheses were further subdivided and effects on Piano Tiles and ODT were checked separately. Since a within-subject design was employed, comparisons between Piano Tiles and ODT regarding flow and physiological arousal measurement are of high value. All results were considered significant at alpha = 0.05.

3.1 Questionnaires

Hypothesis 1: *The two games induce a subjective experience of flow.* The data of 25 participants assessed by the questionnaires were used for this analysis.

H1a: *The game Piano Tiles shows an effect of flow that is significantly greater than zero and the second half of the game is more flow inducing than the first half.* To test these hypotheses averages per participant across all games were computed. Overall mean as well as the mean differences in the questionnaire data (Table 1) between first and second half were analyzed. A one-sample t-test was used to analyze the overall mean and a paired-samples t-test to compare overall flow scores in the first and second half of the game. Further paired-samples t-tests for the separate questionnaire items were conducted in order to see which items differed the most between first and second half.

H1b: *The effect of ODT on flow is significantly greater than zero.* In order to assess if the ODT induced a flow experience, the 15 questionnaire items (Table 1) were classified into competence, flow and challenge. The scores were averaged per participant across all staircases a participant played. Followingly, one-sample t-tests were conducted for competence, flow and challenge. To gain a deeper insight into the particular flow aspect, the 5 items coding flow were also analysed separately.

H1c: *Piano Tiles is more flow inducing than the ODT.* To test this hypothesis the average of the five questionnaire items over the first and second half of Piano Tiles was compared to the average of the same five questionnaire items coding flow in ODT over all staircases. Furthermore, analogous to the analysis of H1a and H1b, the items coding flow have been analysed separately.

H1d: *There is a positive correlation between experiencing flow in Piano Tiles and ODT.* To test this hypothesis the average of the five items over the first and second half of Piano Tiles was correlated with the average of the corresponding five items across all staircases of the ODT.

3.2 Physiological Arousal Measurement

Hypothesis 2: *There is an association between flow and physiological arousal measurements.* To analyse this hypothesis, the findings of hypothesis 1 were incorporated and further data from the HRV measures were used. After exclusion of three participant's HRV data, the analysis was conducted with data of 22 participants. The analysis of SCR was taken out due to a high variability and randomness in data due to noise. Therefore, only HRV was considered in the following analysis.

H2a: *As flow increases in Piano Tiles with time, the heart rate variability is greater during the first half than during the second half.* Participants played as many games as possible in the given 20min. For the analysis of HRV, the first and last game a participant played was analysed for first and second half respectively. Paired-samples t-tests for the change of HRV within games were conducted and the mean difference in HRV change between games was compared. Additionally, HRV was correlated with flow questionnaires.

H2b: *With ten or more consecutive items in the ODT in a row the subjects were assumed to be in flow. Since flow increases over time, the heart rate variability is expected to be unequal during the first and the second half within these flow periods.* This hypothesis could not be tested due to lack of information about the HRV in the ODT.

H2c: *There is a positive correlation between HRV in Piano Tiles and HRV in ODT since the effects of both games should be equally flow inducing, and so equally reduce HRV.* This hypothesis could not be tested due to lack of information about the HRV in the ODT.

3.3 Memory Recognition

Hypothesis 3: *There is a positive association between flow-state and memory.*

H3a: *An increase in flow, as measured by grating performance, is accompanied by an increase in memory performance of items presented during that flow-state.* This hypothesis was tested by classifying ten or more consecutively correct items in the ODT as a flow-state. Memory recall was compared between first and second half of these flow-states with paired samples t-tests. Since participants completed four runs of the ODT, each ending with a memory test, the averages of all runs were compared. Further, since flow was assumed to be greatest in the last run, the last run was analysed separately for memory recall during first and second half of flow-states.

H3b: The overall grating performance, associated with being in the flow, is positively correlated with memory performance. This hypothesis was not tested separately since the descriptives already showed a clear trend in the opposite direction.

4 Results

4.1 Questionnaires

H1a: The one-sample t-test, checked for normality, showed that the overall mean score of the flow questionnaire in Piano Tiles (mean 2.55, SD 0.67) is significantly greater than zero (t[24]=19.10, p <.001). Further, the mean flow score increased from the first half of the game (2.45, SD 0.73) to the second half (2.81, SD 0.70). A paired samples t-test showed that this increase was significant (t[24]=-3.20, p <.002). Normality was not violated as shown in the Shapiro-Wilk Test for normality (p <.096), and the test would be considered robust against any violation due to a sample size of 25. The increase in perceived flow from first to second half can be seen in Figure 8.

Furthermore, the separate paired t-tests for each questionnaire item showed that the difference from first to second half was the greatest for the item 'lost connection with the outside world' (first half: mean 1.83, SD 0.97; second half: mean 2.23, SD 1.15) with a Cohen's d of -0.63. Followed by the items 'losing track of time' with a Cohen's d of -0.61 (first half: mean 1.99 SD 1.03; second half: mean 2.54 SD 1.05) and 'forgot everything around me' with a Cohen's d of -0.61 (first half: mean 2.19 SD 0.96; second half: mean 2.67 SD 1.05). Therefore it can be said, that Piano Tiles clearly induced a subjective feeling of flow which significantly increased during the game.

H1b: Classifying the questionnaire items showed that flow had the highest mean value (2.66, SD 0.75), followed by competence (2.60, SD 0.59) and challenge (1.87) (Figure 9). However, the flow score also showed the highest spread as indicated by the highest standard deviation.

The one-sample t-tests for flow, competence and challenge showed that the mean scores on the questionnaires were significantly greater than zero (flow: t[24]=17.74, p <.001; competence: t[24]=22.12, p<0.001; challenge: t[24]=18.20, p<0.001). A separate analysis of the 5 items coding flow revealed that participants seemed to be especially "fully occupied with the task" (mean 2.99, SD 0.68) and "deeply concentrated on the task" (mean 2.75, SD 0.84) and rather sparsely experienced a "loss of connection with the outside world" (mean 1.43, SD 0.91). Based on these results it can be assumed that the ODT was successful in inducing a subjective feeling of flow.

H1c: Comparing the flow questionnaire of the two tasks showed that the average flow score for ODT (2.69, SD 0.76) was slightly higher than in Piano Tiles (2.55, SD 0.67). However, a look at the distribution plots shows an abnormal distribution of flow scores of the ODT (Figure 10). The analysis of the separate items revealed that the different tasks have different foci. Whereas participants in Piano Tiles scored especially high on 'forget everything around me', 'lose track of

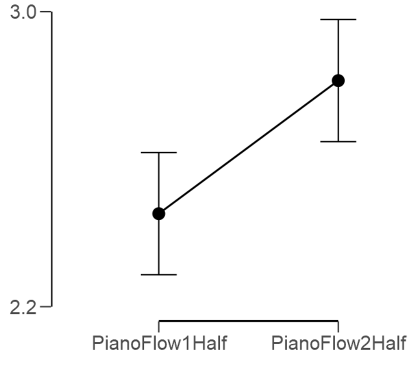

Figure 8: ***The increase in perceived flow***. *The average of questionnaire scores per participant for all games increases significantly (t[24]=-3.20, p <.002) from the first half to the second half of Piano Tiles.*

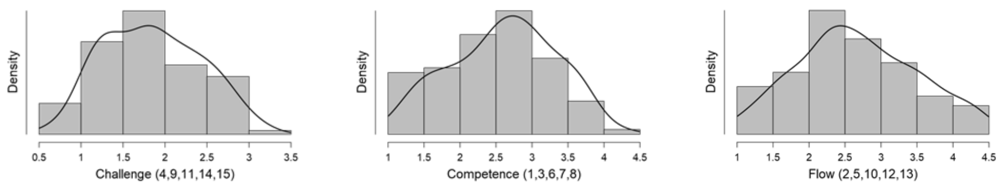

Figure 9: ***Density distributions of Questionnaire answers given for ODT***. *Questionnaire data was classified in challenge, competence and flow.*

time' and 'connection with the outside world' towards the end of the game, the ODT rather induced states of 'being deeply concentrated' and 'being fully occupied with the task'. Furthermore, it has to be noticed that the flow scores of Piano Tiles are averages of the first and second half. When only the flow scores of the second half were taken into account (Figure 11), Piano Tiles yielded a flow score mean of 2.81 (SD 0.70), thereby being slightly higher than the ODT. Taken these results together, it cannot simply be assumed that Piano Tiles was more flow inducing than the ODT as was previously expected, but rather that the two tasks cover different aspects which are all relevant for a flow experience.

H1d: As visualized in Figure 12, a positive correlation between experiencing flow in Piano Tiles and ODT was found (Pearson's r = 0.38, p = 0.031). This shows that participants who experienced higher flow states in one task tended to do so as well in the other.

4.2 Physiological Arousal Measurement

The second aim of this research was to find a physiological arousal measure of flow. Contrary to expectations, no consistent negative association between flow-states and HRV could be found.

H2a: Comparing the first and last Piano Tiles games a participant played showed that the average play duration increased significantly from 105 (SD 52.23) to 156 (SD 51.12) seconds (t[22]=-5.08, p<0.001). Contrary to expectation, HRV increased within games (Table 2). It was expected, that as flow increases within a Piano Tiles game, that the HRV is greater during the first half than during the second half of the game. However, the found trend in the opposite direction was not significant (first game: t[22]=-1.58, p=0.128; last game: t[22]=-1.19, p=0.246). Further, the mean change of HRV within first (0.04, SD 0.11) and last game (0.03, SD 0.10) was not significant (t[22]=0.30, p=0.770). From these results, it cannot be concluded that HRV decreases

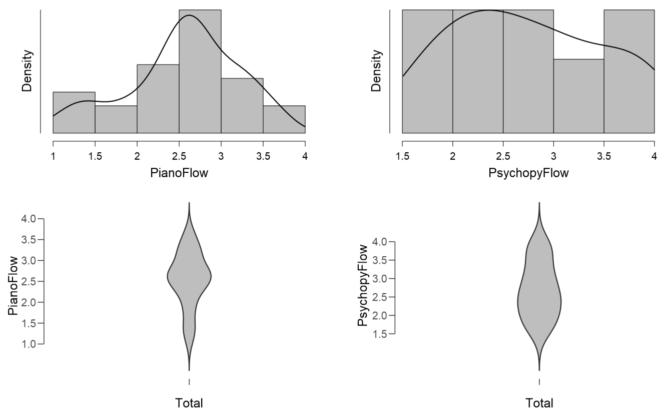

Figure 10: ***Density distributions and Box Plots (Violin) of flow scores in Piano Tiles and ODT***. *The average of 5 items coding flow in both questionnaires was computed. The average flow score is higher for ODT but its distribution of not normal and shows a high spread (mean 2.69, SD 0.76).*

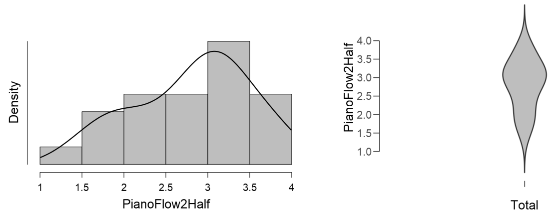

Figure 11: ***Density distribution and Box Plot (violin) of average flow scores in Piano Tiles.*** *Here the average was computed of all Piano Tiles games but only of the second half and is therefore higher (mean 2.81, SD 0.70).*

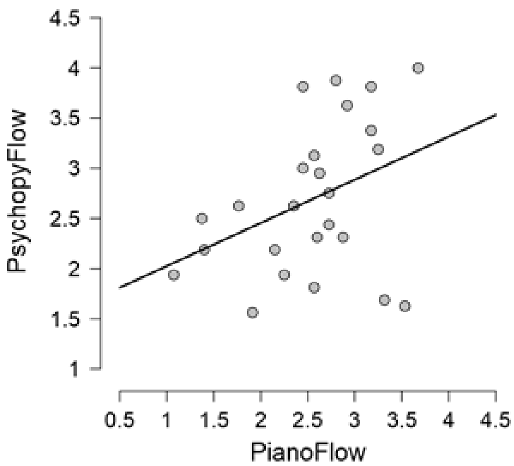

Figure 12: **Scatterplot of flow scores in Piano Tiles and ODT.** *Flow scores of Piano Tiles (X-axis) and flow scores of the ODT (Y-axis) with a regression line, showing that perceiving flow in one of the tasks is highly correlated with perceiving flow in the other task (Pearson's r = 0.38, p = 0.031).*

within a game or across games.

Furthermore, no correlation between the difference in game duration and difference in the increase of heart rate variability between games was found (r=0.12, p=0.592). Correlating the heart rate variability with the corresponding flow questionnaires showed for three of four correlations a significant relation (first game, first half: r=0.57, p=0.006; second half: r=0.13, p=0.570; last game, first half: r=0.55, p=0.008, second half: r=0.40, p=0.068). This shows that the higher participants perceived flow, the higher their HRV (Figure 13).

H2b and **H2c** have not been analysed due to missing HRV data of the ODT (see section 3.2 for details).

Piano Tiles Game	HRV	SD
First game, First half	0.05	0.03
First game, Second half	0.06	0.05
Last game, First half	0.04	0.03
Last game, Second half	0.11	0.15

Table 2: ***HRV during Piano Tiles.*** *In contrast to expectations and prior findings HRV increased within games, from first to second half. HRV also did not decrease across games, from first game to last game.*

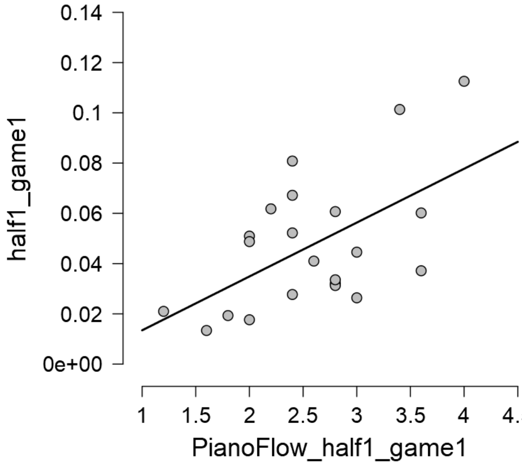

Figure 13: ***Scatterplot of flow questionnaire scores and HRV***. *On the X-axis the flow questionnaire scores of the first half of the first Piano Tiles game are shown. On the Y-axis the corresponding HRV averages of that game during the first half are depicted. The regression line shows the significant correlation (r=0.57, p=0.006).*

4.3 Memory Recognition

The third aim of this research was to find a relationship between being in the flow and memory performance.

H3a: It was expected that memory performance is higher in the second half of a flow-state than in the first half. Overall, across all four runs of the ODT, memory recall increased from 49% (SD 18%) in the first half of flow-states to 51% (SD 13%) in the second half of flow-states (Table 3). Slightly higher percentages for memory recall could be found for the last run a participant absolved (Table 3). However, memory recall increase from first to second half of flow-states was not found to be significant (All runs: t[22] = -062, p=0.539; Last run: t[22] = -0.20, p=0.85).

H3b: Across all four staircases, participants had 66.22% of the memory items correct which were previously shown at a correct grating response, but 77.60% of the memory items previously shown at an incorrect grating response were later recognized correctly. The overall values were assessed by averaging all performance values and can be seen in Table 4. In the first staircase the memory values were 65.44% for grating done right and 77.60% for grating done wrong. The difference between these proportions reached its peak in the third staircase (62.73% and 89.02%). Over staircases, a positive trend was visible in memory performance for the items shown at gratings previously done wrong, from 77.60% to 86.41% .

ODT (run, part)	correct memory recall	SD
All runs, First half	49%	18%
All runs, Second half	51%	13%
Last run, First half	54%	27%
Last run, Second half	56%	28%

Table 3: ***Memory Recall in the ODT.*** *Memory recall in percentage of items presented in the first and second half of classified flow-states (10 or more correct items in the ODT in a row). A small but insignificant increase in correctly recalled items can be seen within and across runs.*

Number of run	Memory recall at correct gratings	Memory recall at incorrent grating
1. Run	65%	78%
2. Run	70%	73%
3. Run	63%	89%
4. Run	67%	86%

Table 4: ***Overall Memory Recall in ODT*** *Memory recall in percentage of items shown during correct and incorrect grating responses. Subjects with less errors (a better grating performance) were assumed to be more in flow. The relative numbers indicate a negative influence of grating performance on memory recall.*

5 Discussion

Main Findings. The aim of the present study was threefold. First, the flow inducing properties of Piano Tiles and the ODT were verified by questionnaires. Both tasks induced flow significantly, with notable differences in competence, challenge and flow components for the ODT. Second, it was examined how flow can be characterized in terms of arousal measurements. To assess HRV of flow states, the Piano Tiles game with increasing task-difficulty, high immersion and prior training session was administered. Results of the Piano Tiles indicate that increasing subjective flow ratings might be associated with increased HRV, contradicting previous findings which found a decrease in HRV (Peifer et al., 2014). However, our results were not significant. Third, a possible association between flow-states and memory improvement was tested during the ODT that allowed parallel presentation of memory items. It was hypothesized, that there is a positive relationship between flow, in-game performance, and memory recognition. Findings suggest that overall less memory items were recognized if the grating responses were correct in the ODT. Contrary to the expectations, overall memory recognition was highest when items were presented at an incorrect response. This memory recognition value increases across runs and was highest in the last game.
Discussion. The analysis of questionnaires indicates that both the Piano Tiles game and the ODT significantly induced flow. As expected, the second, more challenging half of each run was significantly more flow inducing than the first half *(Figure 8)*. Furthermore, participants ratings on the items 'fully occupied with the task' and 'deeply concentrated on the task' were much higher after the ODT, compared to Piano Tiles, in which 'forget everything around' them, 'lose track of time' and 'connection with the outside world' were rated higher. Since flow is not a uniform concept, averaging flow values between different dimensions might not capture specific aspects of flow with different implications for flow characterization. These findings show that components of flow differ remarkably among tasks, which should be taken into consideration for future research.

As hypothesized in H1d, a significant correlation between overall flow ratings of Piano Tiles and the ODT was observed. This suggests that participants who experience more flow in one task show a similar tendency in the other task *(Figure 12)*. These findings are in line with previous research that shows high interindividual variability in flow proneness related to higher scores on extraversion, agreeableness and openness to experience (Ullén, Harmat, Theorell, & Madison, 2016). Since openness is associated with physiological arousal measurements (Zohar, Cloninger, & McCraty, 2013), individual differences, flow perception and proneness should be incorporated in future studies.

Subsequently, the present study investigated whether states of increased flow are associated with changes in HRV. Contrary to the expectations, significant positive correlations between flow questionnaire and HRV was found, indicating that higher subjective ratings of flow are accompanied by higher HRV between participants. These findings contradict previous research that shows both a linear and inverted-U relationship between HRV and flow (Keller, Bless, Blomann, & Kleinböhl, 2011). In theory, it is plausible that flow raises with increased arousal and sympathetic activity until a threshold is reached. Subsequently, the level of flow decreases while the arousal continues to increase (Peifer et al., 2014). An additional possibility is that during states of increased flow, increased allocation of cognitive resources on Piano Tiles might decrease overall mental workload. This may lead to a relaxation effect and increased parasympathetic modulation, resulting in increased HRV (Keller et al., 2011).

Finally, a positive relationship between flow, in-game performance and memory recognition has been hypothesized. Results show that memory recognition was highest of items previously being presented during an incorrect grating response. Assuming that participants experience more flow in periods of correct grating responses, an incorrect grating response possibly leads to an abrupt disruption of flow. This surprising transition between high-flow and low-flow appears to lead participants to reallocate attentional resources on the memory item, thereby improving memory formation in that particular moment. However, further research is needed to clarify the effects of transitions between flow states.

Theoretically, flow is an intense state immersion in the moment itself, which does not directly require learning of task-irrelevant material. In fact, a relation between high performance and suppression of task-irrelevant material has been observed (Vidnyánszky & Sohn, 2005). Therefore, perceptual focus on the task may simply not allow memory formation to increase in flow states. However, the results show that short disruptions of periods of high performance and increased skill-task matching are beneficial for task-irrelevant memory formation. This might have relevant implications in instructional game development.

Limitations. Several limitations need to be considered when interpreting the results. First, in the present study, flow has been treated as a continuous concept with varying degrees of intensity of subcomponents assessed with a questionnaire as criterion measure. Therefore, flow has not been manipulated directly, but results from the participants' efforts to get into flow. The direction of effects remains questionable due to the fact the relationships between flow and HRV and memory recognition are purely correlational.

Second, as mentioned before, the presented memory items in the ODT were not relevant for the task itself and participants were instructed to solely focus on the ODT. Presenting task relevant items during periods of increased flow, possibly shows different results, since they are connected to intensive immersion and the experience of flow itself. Furthermore, the employed forced choice memory recognition task assessed only episodic memory. The relation of flow and memory possibly differs depending on episodic or procedural learning of task-relevant or irrelevant stimuli.

Third, since the statistical analysis of the present design was rather limited, the possibility of data loss due to too many averages taken between games, staircases and questionnaires remains. Employing more sophisticated analyses, for example, multi-level correlations for each participant, potentially provides a better understanding of the relationship between variables associated with flow. Furthermore, an analysis of the HRV in the ODT might reveal different results because it assesses others aspects of flow than Piano Tiles as described earlier.

Implications. To conclude, the present findings can be beneficial for future research that aims at discovering the physiological aspects of flow states to find a more objective measure of flow and understand associated mechanisms such as mental workload. It is advisable to incorporate specific kinds of learning procedures and how they relate to different aspects of flow. Further, future research should clarify the association between flow and physiological measurements while taking individual differences in flow perception and proneness into account. Additionally, the current results regarding the link between memory and flow state disruption may provide a direction for further investigations. There might be a negative connection between brain plasticity and flow, leading to a memory performance that worsens with an increase in flow. However, future studies need to test for short- and longterm memory effects. All together, further research into the relationship between flow states and memory is of high practical value for educational settings, such as educational gaming which aims at connecting entertaining games with learning experiences. Due to the intrinsically rewarding nature of flow, educational games utilizing flow states or as here firstly suggested utilizing disruptions of flow states, could be highly useful in primary or middle school settings.

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