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Physiological Data Acquisition for Deeper Insights into Prototyping

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Abstract
Based on the work of Steven P. Dow & Scott R. Klemmer, "*The efficacy of prototyping under time constraints*", a confirmatory experiment was conducted and two additional questions were investigated in a hypotheses generating, explorative way: How does iterating ideas affect the stress level of the participants while explaining their final design? And; Does the workspace setup influence the activity level of the participant while designing a prototype? The answers were found with the help of physiological data acquisition (electrocardiogram and acceleration). Our results confirm the previously conducted study. The data also suggests that the stress level during the interview is affected: Participants who were able to test their designs show in average a decreasing stress level, compared to participants who were not allowed to test where an increase thereof can be observed. Furthermore, the results show that the workspace setup influences the activity level of the participant.

Keywords: Prototyping, Iteration, Physiological Data, Stress, Bias Towards Action

1 Introduction

Prototyping is at the core of product design and development. To some practitioners and researchers the ability to repeatedly try and obtain feedback through rapid prototyping rounds is essential it seems. The latter has been established, amongst others, by Dow & Klemmer whose work we continue[1] by means of an explorative experiment that operationalizes the effect of an iterative prototyping product development process vs. a planning focused development process by means of a controlled and physiological sensor monitored egg drop task. The study is constructed as confirmatory to [1] and expands the same by also including

[1] Due to page limitations we kindly ask to consult [1] for a discussion on the the value and manner of executing protoyping as well as its canonical steps: envisioning possibilities, creating a prototype to embody a possibility, getting feedback about the prototype, and reevaluating constraints [2].

stress and workspace as independent variables. The egg drop task challenges individual participants to come up with a design that protects a raw egg from being damaged after a free-fall from increasingly high levels. A predefined set of materials and a limited amount of time are given to fulfill this task. Half of the participants (iteration group) have the possibility to test their prototypes during the design phase, whereas the other half (non-iteration group) only has one egg available and therefore is not allowed to perform any tests. All participants have to estimate their performance before and after the design phase. This individual confidence level, as well as the maximum successful drop height, are recorded.

1.1 Given Results and Confirmatory Study

[1] were able to show that participants in the iteration group reached in average a 85% higher score in the free-fall test than the participants in the non-iteration group (186cm vs. 101cm). Furthermore, the confidence level of the participants who were able to iterate increased in average by 44% (125cm before, 180cm after). Participants in the reference group showed in average a confidence level of 95cm, which stayed constant throughout the test. Table 1 gives an overview of the given results. For our experiments we repeated the egg drop experiment in the same way and were able to confirm the results from the previous study.

Table 1 Given Results: Highest drop height reached and the confidence level before and after designing and building the device. Data from [1].

<table>
<tr><th colspan="2"></th><th>Non-Iteration</th><th colspan="2">Difference</th><th>Iteration</th></tr>
<tr><td colspan="2">Final Height</td><td>101cm</td><td colspan="2">+85%</td><td>186cm</td></tr>
<tr><td rowspan="2">Confidence Level</td><td>Before</td><td>95cm</td><td rowspan="2">+0%</td><td rowspan="2">+44%</td><td>125cm</td></tr>
<tr><td>After</td><td>95cm</td><td>180cm</td></tr>
</table>

1.2 Stress due to Uncertainty

It has been shown that not only limited amounts of time induce stress on people but also failure in combination with low self-esteem and uncertainty. The latter has been shown in various studies, usually linked to patients and the amount of information they are given during their illness [3-4]. One characteristic of an increased stress level is an increase of the heart rate [5]. To answer the question of how uncertainty during prototyping affects the stress level a sensor recorded the electrocardiogram (ECG) and acceleration values of the participant during the whole experiment. The combination of these two signals can reveal whether or not an increased heart rate is due to physical activity or due to other factors. We analyzed the heart rate of the participants during the interview that takes place before the final drop test. During the interview the participant has to explain the final design and answer several questions regarding various factors that influence the final score, e.g. "How do you think will your design behave during the free-fall? Will it turn upside down?". Our results show that the participants of the iteration group in average have a decreasing heart rate, unlike the participants of the non-iteration group who show an increasing heart rate.

1.3 Bias Towards Action

In the field of ergonomics, a lot of research is done in order to assess the influence of light, temperature and other external factors on the well-being of an employee [6-7]. Our experiment offered the opportunity to measure the influence of the workspace setup on the activity level of the participant. Half of the iteration group had a setup that supported an upright body position while working, whereas the other half used a setup that strongly suggests working while being seated. The number of iterations each participant went through was recorded. Participants using the standing workspace setup tested more often than the sitting participants.

2 Method

By repeating the experiment of [1] – where the materials list and the procedure is taken from - we first of all wanted to perform a confirmatory study. Furthermore, the experimental setup allowed for testing the following two hypotheses:

- Participants who were allowed to test their designs will show a lower stress level during the interview.
- Participants who are allowed to test their designs and have a workspace setup that supports a bias towards action (standing upright while working) will perform more tests than participants who are sitting comfortably while working.

2.1 Setup

The experiment took place in our ideation space at NTNU Trondheim. The drop-zone for testing was only a few steps away from the workspace itself to enable for quick testing during the design phase. The two different workspace (sitting and standing) setups are described below and shown in Figure 1.

2.1.1 Participant Sitting

Half of the participants of the iteration group had a workspace setup that strongly supported working while being seated. A table (wooden board resting on two sawhorses) with a low height and a matching seating option were used. The chair used is the model *Capisco* from Håg and it is, according to the description, ideal for this purpose: *If you are into innovation, HÅG Capisco is the office chair for you* [8].

2.1.2 Participant Standing

The other half of the participants in the iteration group had the setup that supports standing while working. The table has a comfortable height of roughly 120cm.

Figure 1 Workspace Setups: The two different workspace setups, for standing participants (left) and sitting participants (right).

2.2 Physiological Data Acquisition

To gather information about the heart rate of the participants they were wearing an ECG sensor throughout the experiments. Additionally, an accelerometer measured acceleration data in all three axis directions (X, Y, Z). Both signals (ECG and acceleration) were stored on a microSD card.

2.2.1 Hardware
The five components that were used and their individual functions are:

- Arduino Uno (ARDUINO, Italy): This micro controller is the core component of the whole setup and runs the program that gathers and stores the data from the entire setup.
- CookingHacks eHealth Shield (LIBELIUM COMUNICACIONES DISTRIBUIDAS S.L., Spain): The eHealth shield can be used as a sensor platform for a wide range of vital data sensors. In this case it amplifies the voltage reading (x300) from the electrodes attached to the skin of the participant.
- Sparkfun microSD shield (SPARKFUN ELECTRONICS, CO, USA): This shield enables data storage on a microSD. In this case it was also used as the mounting platform for the accelerometer.
- Sparkfun Triple Axis Accelerometer - MMA8452Q: This sensor measures the acceleration in all three axis directions.
- 9V battery: The battery powers the unit.

The individual components and the complete experiment setup can be seen in Figure 2.

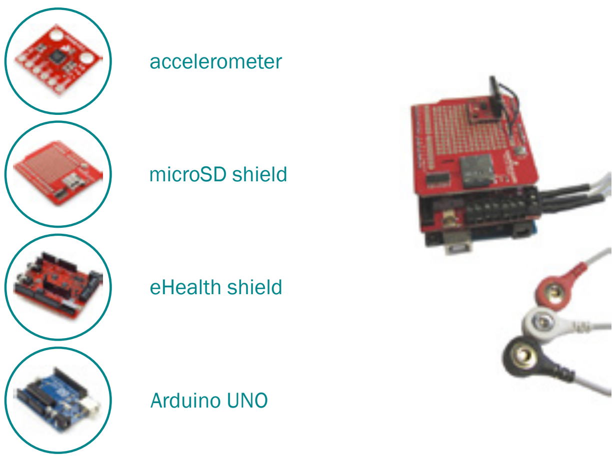

Figure 2 Physiological Data Acquisition: The individual components and the complete sensor package [9-12].

2.2.2 Software
The code running on the Arduino was kept as simple as possible in order to reach a high sampling rate (~50Hz). With every iteration the three acceleration values and the voltage reading from the ECG unit are stored on the microSD card.

2.2.3 Usage
The participant had to attach three electrodes (+, −, and neutral) to his body. During the experiments the sensor package was placed in an antistatic bubble wrap bag and was attached with a quick release strap to the belt loops of the participants. This setup proved not only easy to be used but also exclusively captures the acceleration data of the hip.

2.3 Materials
One set of the following materials was allowed for the final design (see Figure 3):

- 8 pipe cleaners

- 8 rubber bands
- 8 popsicle sticks
- 1 10x20cm poster board
- 1 10x15cm flat foam
- 1 sheet of tissue paper
- 30cm scotch tape

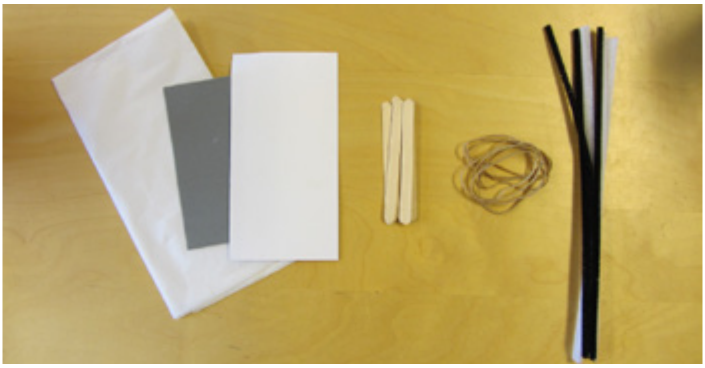

Figure 3 One Set of Materials: (FLTR) Tissue paper, flat foam, poster board, popsicle sticks, rubber bands, pipe cleaners (scotch tape not shown).

2.4 Participants

Our number of participants was N=13 and the average age of the participants was 21.8 years. The iteration group consisted of 6 participants and the non-iteration group of 7 participants. Only 3 participants had previous experience with the egg drop task, none of them with such a limited amount of materials and time though. The participants were uniquely recruited amongst students in their 4th semester of mechanical engineering studies at NTNU as, by passing many exams, they have already shown a high level of motivation for engineering but are not yet focused on only one specific direction thereof.

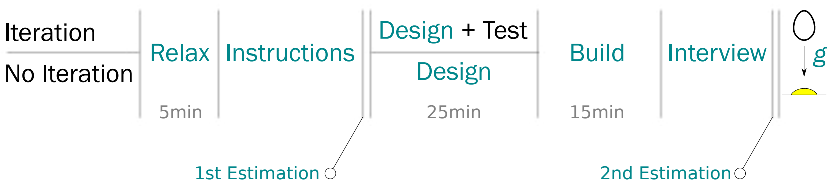

Figure 4 Timeline of the Experiments.

2.5 Procedure

The participant first voluntarily signed a document stating that they allow us to record their data. The participant then attached the three electrodes for the ECG and the now activated sensor package. In order to make the participants feel more at ease and to get their resting heart rate they took a seat and watched a five-minute segment of a relaxing video. After this the participant received the instructions for the task and was shown a complete set of materials. At the drop zone the participant had to give the first estimation of the reachable height (noted as *confidence level before*). The participant then had 25min time to design a device that will protect the egg. Every 5min the participant got informed about the remaining time and was encouraged to test the design (iteration group only). During the design phase the participant had no material restrictions, meaning that the researcher provided more material whenever it was needed. Once the design phase was over the table was cleared from any remaining materials and the participant got a fresh set of materials and 15min time to build the final design. Following the build phase the participant had to explain the final design to the researcher. The interview was completed when the participant was unable to add more information. After estimating the maximum reachable height a second time (noted as *confidence level after*) the device was tested by dropping it from increasingly high levels: Starting at 30cm, the drop height was increased by steps of 30cm until the egg cracked. Figure 4 shows the timeline of the experiments.

2.6 Post Processing

The data gathered by the sensor package consists of a voltage reading in V across the electrodes, three acceleration values in g from the accelerometer, and a timestamp of each iteration. Post processing of the raw data from the sensors was done using a program written in MATLAB (MATHWORKS, MA, USA). The program sums up the absolute values of the three acceleration values, applies various filters to the ECG signal, detects voltage peaks indicating a heart beat and calculates the heart rate based on this information.

3 Results

This section deals with the outcome of our experiments and is segmented into the results of the confirmatory study and the results that answer our hypotheses. Due to the small number of participants we did not perform any significance tests and only claim internal validity for our results.

3.1 Confirmatory Study

With our experiments we were able to confirm both results given by [1]: The participants in the iteration group reached in average a higher final height in the drop test and their confidence level increased. Table 2 summarizes the results.

3.1.1 Results: Maximum Drop Height

Both groups include cases worth highlighting: One participant in the iteration group, who had no previous experience with the task, built such a great device, that it was impossible to break the egg, even when dropping it from the ceiling (510cm). We therefore took this architectonical limitation as the maximum value, even though the real number might be a lot higher. In the non-iteration group three participants broke their one and only egg by testing their design on the worktable. All of them were given a replacement egg for the final drop, even though this is not according to the rules.

Table 2 Confirmatory Study Results: Comparison of the maximum drop height and the confidence level of the two groups. *Three participants in the non-iteration group tested their prototypes on the table during the design phase and subsequently cracked their eggs. Their official result therefore was 0cm. The value in brackets is calculated with the heights they reached with a replacement egg.

<table>
<tr><td colspan="2"></td><td>Non-Iteration</td><td colspan="2">Difference</td><td>Iteration</td></tr>
<tr><td colspan="2">Final Height*</td><td>69cm (103cm)</td><td colspan="2">+154% (+70%)</td><td>175cm</td></tr>
<tr><td rowspan="2">Confidence Level</td><td>Before</td><td>141cm</td><td rowspan="2">-3%</td><td rowspan="2">+18%</td><td>135cm</td></tr>
<tr><td>After</td><td>137cm</td><td>160cm</td></tr>
</table>

3.1.2 Results: Confidence Level

The participant gave the first estimation (*confidence level before*) after receiving the instructions but before starting the design phase. The estimation *after* was given when the building phase was over. The confidence level of the participants in the iteration group increased by 18%, whereas the confidence level of the participants in the non-iteration group decreased by 3%.

3.2 New Results

The new results contain the answers to the hypotheses stated above. The physiological data recordings proved to be extremely useful and revealed information about the activity level and stress level of the participants. Figure 5 shows the resulting data from one participant (p4) who was part of the iteration group and using the sitting workspace setup. This data set was chosen as an example because p4 was exceptionally motivated and had phases of both, intensive physical activity and high stress levels, both clearly visible in the plots.

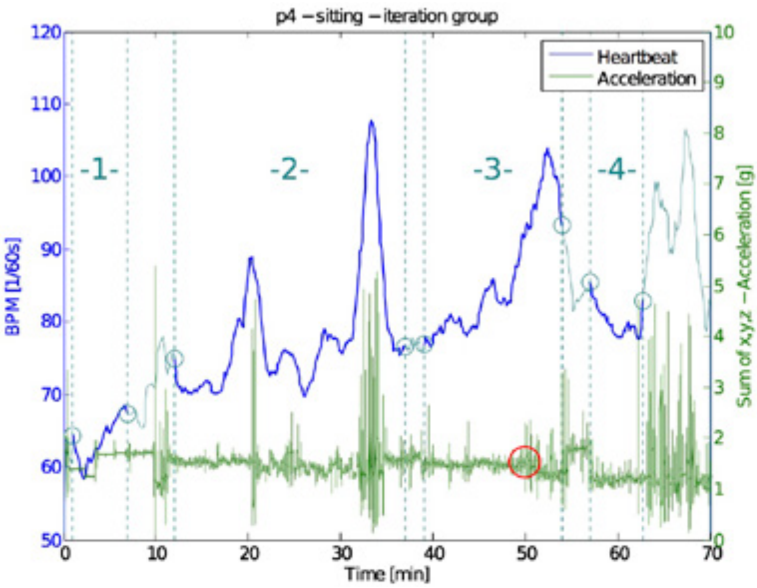

Figure 5 ECG and Acceleration Sample: The blue graph shows the heart rate throughout the experiments and the green graph shows the sum of the absolute values of the acceleration data along the three axis (X, Y, Z). The four phases are: 1 - Relaxing Movie, 2 - Design Phase incl. two test runs, 3 - Build phase with intense stress due to time pressure towards the end, 4 - Interview. The red circle marks the spot where the participant jumped up from his seat and shouted, "I'M SO STRESSED OUT! I'M SHAKING! MY HEART RATE IS THROUGH THE ROOF!".

Table 3 Number of Iterations: Comparison of the number of iterations performed by participants in the iteration group while using different workspace setups.

Standing		**Sitting**	
Participant	*Nr. of Iterations*	*Participant*	*Nr. of Iterations*
p2	5	p4	2
p6	4	p8	4
p10	4	p12	4
Average Standing	**4.33**	*Average Sitting*	**3.33**

3.2.1 Bias Towards Action

As described before, our hypothesis was that the workspace setup has a major influence on the activity level of the participant. We noted the number of prototypes each participant in the iteration group tested during the design phase. The results are listed in Table 3. The participants that were standing during the experiment tested their design in average 30% more often than the sitting participants (4.33 iterations vs. 3.33 iterations).

3.2.2 Stress Level

In order to describe the behavior of the stress level of a participant during the interview the heart rate was averaged over two 15s periods: The first one starts with an offset of 5s after the beginning of the interview, the second one ends 5s before the end of the interview. It has been shown that one characteristic of an increased stress level is an increase of the heart rate [5] and that such short slices of physiological data are sufficient in order to predict or assess the emotional state of a person [13-14]. The interviews lasted in average for 3.9min. The results reveal that only 20% of the participants in the iteration group had an increasing heart rate over the period of the interview, compared to 80% of the participants in the non-iteration group. Also, the heart rate of the participants in the iteration group decreased in average by 2.13%, whereas the heart rate of the participants in the non-iteration group increased in average by 6.82%. Table 4 contains the heart rate values of the individual slices.

Table 4 Stress Level. Comparison of the heart rate at the beginning and at the end of the interview. The heart rate is averaged over two periods of 15s: The first one starts 5s after the start of the interview, the second one ends 5s before the interview is over. p1, p2, and p3 are excluded from the results as their ECG was running on an older, slower code which resulted in insufficiently precise data.

Iteration Group					
Participant	*BPM Interview Start [1/min]*	*BPM Interview End [1/min]*	*BPM Abs. Difference [1/min]*	*Rel. Difference [%]*	*Trend*
p4	84.7	82.2	-2.5	-3.0	-
p6	80.7	78.7	-2.0	-2.5	-
p8	85.0	79.4	-5.6	-6.6	-
p10	77.4	78.8	+1.4	+1.8	+
p12	91.9	91.5	-0.4	-0.4	-
Average			**-1.8**	**-2.1**	**20% +**

Non-Iteration Group					
Participant	*BPM Interview Start [1/min]*	*BPM Interview End [1/min]*	*BPM Abs. Difference [1/min]*	*Rel. Difference [%]*	*Trend*
p5	92.2	93.8	+1.6	+1.7	+
p7	100.7	99.6	-1.1	-1.1	-
p9	76.1	82.1	+6.0	+7.9	+
p11	77.0	88.3	+11.8	+15.3	+
p13	80.1	88.3	+8.2	+10.2	+
Average			**+5.3**	**+6.8**	**80% +**

4 Discussions, Conclusion and Outlook

Even though the number of data points is small, these results reveal interesting starting points for further studies.

4.1 Discussion: Confirmatory Study

Both groups, iteration and non-iteration, reached in average a lower height than the participants in [1]. The relative difference between the two groups, however, is almost twice as big: +152% in our experiments vs. +85% in the given results. The iteration group in our experiments did not show such a strong increase in the confidence level though: +18% in our experiments vs. +44% in the given results. The non-iteration group showed a very similar trend as in the given results: -3% in our experiments vs. 0% in the given results. The differences would most likely become smaller in a study with more participants. Nevertheless, our results show a trend that confirms the outcome of the previous study: Iterating ideas and testing prototypes during the design phase does increase the quality of the final product that is made from the same materials and designed within the same timeframe. An observation worth mentioning are the three participants of the non-iteration group who cracked their egg: They all had clear instructions that they only have one egg and yet they all decided to test their idea on the table during the design phase, rather than finishing a product with an unknown performance. They were all given a fresh egg in order to allow them to finish their design and compete in the final contest - all of them completely changed their designs and reached heights between 60cm and 90cm, which evidently is a lot better than 0cm. This allows us to see how strong the urge to test was amongst the participants and how much information can be gained by just one test run. The outlier in the iteration group clearly is participant p4 who reached 510+cm. This participant is included in the results as he shows that extreme heights are possible with the same set of materials and within the same timeframe that everybody else had available.

4.2 Discussion: Bias Towards Action

We were able to show that participants who are standing while working on their ideas tested 30% more often than sitting participants. One might argue that this outcome is the defined by only two participants, p2 with 5 iterations vs. p4 with 2 iterations. However, experiments that allow a longer time for designing and testing the ideas would most likely result in a bigger difference between the two different workspace setups.

4.3 Discussion: Stress Level

The results show that in average the participants of the iteration group are less stressed while explaining their designs than the participants of the iteration group. One explanation for this is their lower level of uncertainty as they have an idea of what the outcome will look like. It might also be due to the fact that they are convinced of the answers they are giving to questions regarding technical details of their design. The participants of the non-iteration group can only answer based on their general experience and quite often they certainly have not taken some factors into account, e.g. whether or not they expect the prototype to flip over during the free fall.

4.4 Conclusion

The physiological data acquisition proved to be successful and revealed new insights into the stress level of the participant. The results show that, for example, an engineer who is working on a new product will not only deliver a better design if (s)he had the chance to test it, (s)he will also be more confident in his product. These results go together with a decrease of the engineers stress level, which could also be the result of the higher confidence. A lower stress level and gained knowledge from previous tests could offer good conditions to find unusual and creative ideas. One stress factor that will never be eliminated though is time pressure. However, our results suggest that a clever setup of the workspace, creating a bias towards action during the design phase, will increase the number of iterations of ideas. We believe that more iterations once again lead to more knowledge and better results. The quality of the final product therefore is directly affected by the setup of the workspace.

4.5 Outlook

Further studies should be conducted with a larger number of participants. Using a set of different design tasks that consist of a similar procedure and have measurable outputs could also show that the results are independent of the task itself. Also, a more extreme difference between the iteration group and the non-iteration group could provoke even clearer results. For example, the non-iteration group could only be allowed to use pen and paper or a CAD software during the design phase. Regarding the workspace setup, further studies should also reveal the importance of the workspace setup along the timeline of a project: Working while standing supports early stage prototyping – but what should the workspace look like to support the later phases of a project? The goal is to create a workspace that adjusts to the current project phase and supports every step from the first prototype to the product launch.

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