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Exploration of Physiological Arousal in Divergent and Convergent Thinking using 2D screen and VR Sketching Tools.

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***Abstract*—Creativity Support Tools (CSTs), like sketching tools, enable designers in their creative activities. As designers may have different needs during different thinking phases, accessing physiological responses in real-time would enable CSTs to better adapt to these different phases. Several studies have focused on either different phases on the same tool or the same phase on different tools. We investigate ways to discriminate divergent and convergent thinking phases using physiological response. We replicated the same experiment with thirty participants each on two different CSTs: in immersive virtual reality and on an interactive whiteboard (2D). We analyzed Heart Rate Variability (HRV) and Galvanic Skin Response (GSR) during a divergent thinking task followed by a convergent thinking task. Our results revealed significant changes in arousal, measured through HRV and GSR, which seem specific to each creative thinking phase. We discuss how each phase can be linked with specific reactions independently of the CST. We suggest that it may be possible to detect a favorable creative state depending on the task being performed.**

***Index Terms*—Creativity; Arousal; Heart Rate Variability; Galvanic Skin Response; Digital tools for creativity**

I. INTRODUCTION

For companies to stay competitive through innovation, creativity is a crucial component during the early phases of the design cycle. Creativity can be compartmentalized in two types of thinking [1]: divergent thinking (which involves generating new ideas and unexpected solutions) and convergent thinking (which consists in narrowing down possibilities and selecting the best answer possible). It is essential not to jump from one creative thinking phase to the next too early in order to stay away from creative fixation that could inhibit creative performance [2], [3].

The early phases of the design cycle [4] often rely on sketching as a crucial tool to rapidly develop and propose new ideas [5]. With the rapid growth of technology, sketching is no longer limited to pen and paper. Frich et al. [6] try to map the landscape of Creativity Support Tools (CSTs) to provide a definition for the Human-Computer Interaction community. They explain that the goal of a CST is to make people more creative more often and reach a tentative synthesis definition: ”A CST runs on one or more digital systems, encompasses one or more creativity-focused features, and is employed to positively influence users of varying expertise in one or more distinct phases of the creative process”.

A large body of literature has been developed trying to compare the different tools and their contribution to the creative process [7], [8]. However, creativity is a complex concept, and while it is possible to use a sketching tool for the entire creative process, it is difficult to identify clearly which affordances benefit which part of the creative process. For example, immersive Virtual Reality (VR) facilitates spatial inspections, leading to improved performance because of its more holistic approach [9]. Furthermore, VR has been shown to induce strong physiological arousal reactions [10].

To better understand how creativity works, part of the literature attempts to analyze its relationship with psychophysiological states. Researchers have primarily explored how arousal and physiological responses may be directly correlated with creative thinking and creative performance [11], [12]. Smart wearables are becoming increasingly popular and encompassing more sensors, including inertial measurement units and physiological sensors, allowing for high-quality recordings while being unobtrusive. With the ability to monitor participants' data naturally, it could be possible to measure and identify their creative thinking phases, enabling a session facilitator to assist them (*e.g.* prevent them from converging too early, or be in a divergent state when asked to refine an idea).

Our goal is to detect physiological arousal responses due to divergent and convergent creative thinking using unobtrusive wearable devices across different CSTs. We designed a study to observe physiological responses as markers of creative thinking phases, and highlight comparable differences between divergent and convergent thinking. Our study consists of a two-phase experiment with two radically different CSTs. Two idiomatic concepts of sketching for creativity: a 3D immersive VR sketching tool and a 2D interactive whiteboard. Both sketching systems offer essentially the same interaction tools and mechanics. The experiment comprises two successive creative thinking tasks: a divergent thinking task based on the Alternative Uses Test (AUT; proposed by [1], with a bike's crankset) followed by a convergent thinking task (refining and studying an established concept). We measure physiological responses through the unobtrusive smart Wearable Empatica E4. For our user study, we recruited 60 participants and separated them into two groups of 30, with each group experiencing only one modality. The novelty of our contribution lies in highlighting the differences between the two phases of creativity in terms of physiological arousal, measured through Heart Rate Variability (HRV) and Galvanic Skin Response (GSR). Moreover, this novelty is combined with our ability to compare results over two different sketching modalities, and different creative tasks.

II. RELATED WORK

A. Divergent and Convergent thinking

As introduced earlier, Guilford [1] theorized the construct of creativity into two measurable cognitive ingredients that individuals experience regularly: divergent and convergent thinking. Divergent thinking is a style of thinking that allows idea generation, in a context where the selection criteria are relatively vague and more than one solution is correct, involving flexibility of the mind. In contrast, convergent thinking represents a style of thinking that allows finding single solutions to a well-defined problem, which requires more persistence and focus.

In a recent meta-analysis, Zhang *et al.* [13] reviewed the underlying cognitive and neurological mechanisms of divergent and convergent thinking. They propose that these two components of the creative process rely on different functional and neural mechanisms, as each possesses unique characteristics and plays different roles in creative production. From their review, they propose a tentative framework to characterize the mechanics of creative cognition in humans. They suggest that brain-activation patterns match the fact that divergent thinking is linked with enhanced flexibility while convergent thinking is linked with enhanced persistence. This review implies that divergent and convergent thinking elicit distinguishable and identifiable neurological and cognitive responses, which could be translated into specific physiological responses measured through other means.

B. Creativity, arousal, and focus

Multiple studies have shown that arousal is linked with creativity. De Dreu *et al.* [14] developed a dual pathway to creativity model. They state that creative fluency and originality are functions of cognitive flexibility, persistence, or some combination thereof. They argue that activating moods help creative fluency and originality and that deactivating moods lead to higher persistence. They state that the effects of mood on creativity cannot be only viewed through activation or positive/negative affect, both have to be accounted for. The effect of mood on creativity is also discussed in a meta-analysis [11], which concludes that creative performance emerges as a result of both affective arousal and regulatory focus.

In a series of studies Loudon & Deininger explored the relationship between physiological responses and creative thinking [15], [16]. Their results suggest that there is a negative correlation between low-frequency (LF) power of HRV and divergent thinking performance. They hypothesize that it might be related to the level of mental workload and attention applied to the task. They also observed significant changes in physiological responses between a relaxed state and high attention states experienced when doing a creative task that result in higher heart rate and lower LF HRV. The results of their studies support the idea that people enter a state of concentration with positive affect during a creative activity and that divergent thinking is correlated with physiological responses.

A more recent study [12] confirms that highly arousing situations, including negative ones such as creative frustration, can even boost creative performance in individuals with specific personality traits.

C. Experimenting with creativity support tools

Most of the studies focus on exploring either one creative thinking phase (divergent or convergent), sometimes using multiple CSTs, or on studying the different phases but with only one CST. However, technologies are evolving rapidly, each one providing specific advantages. Mixed Reality technologies are promising tools to boost creativity [8], [17]. Virtual Reality, in particular, seems to be very beneficial to creativity when compared to more traditional medium, due to its novelty and high immersive nature. Could the high stimulating effects of VR, demonstrated for example by [18], be factors in changing intrinsic creative process as a whole? Virtual reality enables specific levers to be activated to promote creativity. Hu *et al.* [19] explain that creativity is often limited by our own mental barriers. They argue that mixed reality (XR) platforms (from augmented reality (AR) to virtual reality (VR)) can help remove those barriers and promote creativity. They argue that the rich and multi-sensory stimuli, embodied cognition, and 3D spatial cognition provided by XR technologies can extend people's vision and idea generation capabilities. In this paper, we will investigate if the same reactions (physiological response) can be observed and linked with a specific creative thinking task (divergent or convergent) when using a VR CST compared to a more traditional CST.

III. HYPOTHESIS

As we demonstrated earlier, multiple studies explored the relationship between physiological responses, arousal, and creative thinking. Most of them explore only one type of creative task at a time. Very few compare the differences between divergent and convergent thinking. Moreover, they often do not rely on CST and rarely on sketching, even if it is a very powerful tool for innovation design. We wanted to explore these unknown points as part of a classical creativity process [1]: production of ideas (divergent thinking) followed by the refinement and solidification of a concept (convergent thinking). As a result, we devised the following hypothesis: *it is possible to discriminate divergent and convergent thinking through physiological arousal, independently of the type of the CST used.*

IV. MATERIALS AND METHODS

A. Participants

We recruited 60 participants for this experiment (15 women and 45 men) aged between 19 and 36 years old (M=22.73, SD=3.522). The recruitment campaign was done by sending emails to the students of the engineering school and to the staff, and with posters displayed at the entrance of the main building (with QR code to register to participate). The participants recruited were mostly engineering students (37), bachelor students (12) and some PhD students, researchers, and human-factor practitioners (11). The participants are fairly young and represent a population that could, in the future, use VR tools in their professional environment.

We conducted our study using a between-subject experimental design. Our 60 participants are divided into two distinct groups of 30. The first group performs the tasks in 3D using the VR setup, while the second group performs the tasks in 2D using the interactive whiteboard. Both groups perform the exact same sets of activities.

To ensure that our groups were comparable, we measured, using custom 1 to 5 Likert scales, the participants level of interest for conception, up-cycling and societal responsibility, in order to measure their intrinsic motivation for the subject. Mann-Whitney test on the results showed no significant differences between our two groups for conception ($p{=}.218$, $Z{=}{-}1.231$; $Md^{VR}{=}4.00$; $Md^{2D}{=}4.00$), nor up-cycling ($p{=}.536$, $Z{=}{-}.619$; $Md^{VR}{=}4.00$; $Md^{2D}{=}4.00$), nor societal responsibility ($p{=}.864$, $Z{=}{-}.172$; $Md^{VR}{=}4.50$; $Md^{2D}{=}4.50$).

Moreover, before the experiment the participants were asked to complete a divergent thinking test [20]. For this test, they were shown a picture of 30 blank circles. Then, using an interactive display, they had 3 minutes to transform as many circles as possible in different concepts or objects. Once they complete this task, they answered a Remote Associate Test (RAT) [21] to measure their convergent thinking. The scores of the divergent thinking test before the sketching activity (drawing with circles) were compared with a Mann-Whitney test which revealed no significant differences between the two groups ($p{=}.756$, $Z{=}{-}.311$) with median scores of 1.861 in VR condition and 1.790 in whiteboard condition. Likewise, the scores of the RAT test were compared with a Mann-Whitney test which revealed no significant differences between the two groups ($p{=}.160$, $Z{=}{-}1.407$) with median scores of 3.00 in VR condition and 4.00 in whiteboard condition.

B. Apparatus

For the VR modality, we used a HTC Vive Pro Eye VR System. We used a customized 3D sketching application developed in our lab. This application allows the user to draw freely in a 3D virtual environment. The user has access to a color palette, different sizes of brushes, and tone palettes. The user can erase part of the sketch, save the current sketch, and load a sketch as well.

For the 2D sketching modality, we used the same computer coupled with a Samsung Advanced Digital Whiteboard, that allows touch screen interaction, sketching, color selection, erasing, saving sketches, and loading sketches. The user has access to a color palette and can draw in different sizes depending on the surface of contact with the screen (hands or pen).

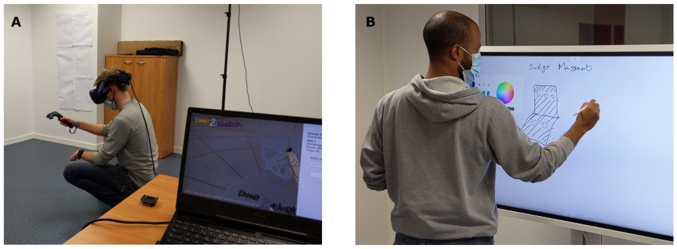

Fig. 1. Examples of users interacting with the sketching CSTs, **(A)** in the virtual reality condition, **(B)** in the interactive whiteboard condition.

Physiological data were recorded using the Empatica E4 smart wristband. We chose the Empatica for its ability to measure Galvanic Skin Response (GSR) and Heart Rate Variability (HRV) and for being a tool that has been validated in multiple studies already [22]–[24].

C. Variables and measures

Using the Empatica E4 smart wristband we recorded both cardiac activity as well as GSR. To extract the different features and analyze the data we used the Python packages [25], [26] and wrote the extra Python script we needed. The data were extracted during the different phases of our experiment (calibration, divergent thinking, and convergent thinking). To compare and analyze our data we computed mean values over the entire period for each phase and each participant.

To select which physiological markers to use and how to derive them to extract physiological arousal, we looked into multiple studies using different physiological markers to measure arousal [27], [28]. From these different studies we found the following markers:

- Heart rate variability is a strong indicator of arousal. We use two markers particularly relevant to our study:
  - Low-frequency band (0.04 - 0.15Hz) of heart rate variability (LF-HRV) is negatively correlated with levels of attention and arousal (an decrease in LF power means an increase in attention and arousal) [27];
  - The root mean square of successive differences of N-N (RMSSDNN) has been found to be positively correlated with arousal [28]. RMSSDNN tends to decrease when working memory load increase however [29].
- Galvanic skin response (GSR) has been demonstrated to be directly positively correlated with arousal, we collected its raw value [30], [31].

To exploit our data despite the interpersonal differences we apply normalization formulas. The LF band is normalized by participants using the high frequency (HF) band with the following formula:

$$LF_{\text{Normalized}} = \frac{LF}{(LF + HF)}$$

Following the work of [31] we normalized the GSR data for each participants using the following equation:

$$GSR_{\text{Normalized}} = \frac{GSR_{\text{t}} - GSR_{\text{min}}}{GSR_{\text{max}} - GSR_{\text{min}}}$$

D. Experimental procedure

Based on this process of [1] and the work of [32] (getting the right design and then the design right) we decided to propose a two-phase creative process: divergent thinking then convergent thinking. One of the most common divergent thinking exercise found in the literature is the AUT [33] during which one is tasked with generating alternative uses to a common object.

First the participants were asked to read and sign, if they accept, a consent form informing them that they are susceptible to be filmed, and that their answers to the questionnaires will be used only in this research and that they can back out anytime they want or don't feel comfortable. They also certified that they did not present heart problems or stereoscopic vision troubles.

Once they signed the consent form, they were asked to answer a demographic questionnaire to gather information about their age, sex, educational background, and their intrinsic motivation regarding the subject (interest for conception, up-cycling and societal responsibility on a scale from 1 to 5) (see Section IV-A).

We then equipped the participants with the Empatica on their non-dominant hand and asked them to try and avoid moving their arm too much to limit movement artifacts altering the data collection. The participants are then explained that they will watch four short clips from movies on a computer, for us to complete a calibration of their physiological data (HRV and GSR). The four clips were taken from the FilmStim database, based on the work of [34]. It is a database of short clips selected to elicit certain types of emotions. We selected the clips 45, 49, 58 and 64, all tagged as "neutral". This added up to a calibration phase of two minutes.

The participants were then asked to complete a divergent thinking test [20] and then answer the RAT [21] to measure their convergent thinking, as presented in Section IV-A.

The participants were presented the setup they were going to use and equipped if necessary (see Figure 1). For the VR experience, the participants first completed a tutorial session during which they were introduced to the different tools they had access to. They could draw freely and once they felt comfortable, they proceeded to the next phase. For the 2D sketching tool the participants were introduced to the different ways of interaction with the screen (how to draw, change color, erase, and save) and were asked if they had any questions regarding the usage of the screen.

The participants were then introduced with the divergent thinking scenario:

> *The collapse has happened, there is no more electricity or fossil energies anymore to power the systems that surround us. Your colony managed to settle near an old cycling spare parts warehouse. The different parts (wheels, saddle, chain...) have already been used to facilitate the life of the colony. There is a huge number of cranksets that has not been used yet. You have to find ways to divert the usage of these cranksets to simplify the life of the colony. Do not limit yourself to feasibility or realism, there are no good or bad ideas.*

The participants were asked to produce one sketch for each idea they had and give them a short description or name. This was based on Guilford's AUT [33]. We let the participants produce as many ideas as possible and they could stop whenever they felt like they were done. If they produced ideas for more than 15 minutes, we informed them that they could record one last idea and proceed to the next phase.

The VR scene took place in an old warehouse with some furniture. A 3D model of the crankset was placed at center of the scene. The participants could draw and move freely around it. This design choice was made to leverage the full potential of VR in its actual usage. For the interactive whiteboard condition, a real crankset was placed next to the board so that the participants could have a visual representation of the object, to create an experience as similar as possible to the VR condition.

After the divergent thinking phase was complete, we introduced the second phase of creativity, which consisted in a convergent thinking task:

> *After the collapse, there has been a rise in physical work and thus a rise in injuries and muscular problems. In this context it is necessary to propose a solution to relieve people of the different pain they experience. So, your colony brainstormed and came to a common idea that seems feasible. They designed a simplistic prototype of a massaging seat using the cranksets. They did not care about the realization and how it was supposed to work. Your goal is to improve the concept, make it functional, study the limitations and its realization.*

For this phase the participants loaded a drawn sketch of the massaging seat prototype. The participants were informed that they could erase parts of the drawing, draw around, modify, or change the concept while still proposing a massaging solution using the crankset as a fundamental part of the system. They had to propose one sketch and explain the main modifications and additions to their final idea. Once they were done, they then saved the sketch, and the creativity experiment ended. We helped the participants remove the equipment and asked them if they had questions about the experiment. The complete procedure lasted for approximately 45 minutes up to 1 hour.

V. RESULTS

We tested the normality of the distribution using the Shapiro-Wilk test before conducting our different statistical comparisons. Whenever the condition of normality was not met, we performed the comparison with non-parametric analysis. For each value considered we compared the evolution of said value between the different phases of the experiment for each group separately: calibration vs. divergent thinking, calibration vs. convergent thinking and divergent thinking vs. convergent thinking. As we believed that the limited sample size of our participants would hinder an objective comparison, we did not statistically compare the two groups' physiological response. We applied a Bonferroni adjustment to the alpha level when comparing the three phases, thus significant alpha level is set at 0.017 (0.05/3).

A. Heart rate variability

TABLE I
MEAN VALUES (STANDARD DEVIATIONS) OF HRV DATA ANALYZED.

		VR 3D Sketching	2D Sketching
RMSSDNN	Calibration	.0513 (.021)	.0623 (.030)
	Divergent	.0793 (.024)	.0914 (.047)
	Convergent	.0758 (.023)	.0747 (.030)
LF	Calibration	.2402 (.086)	.2573 (.115)
	Divergent	.4236 (.098)	.3967 (.150)
	Convergent	.3506 (.152)	.3625 (.186)

Table I shows all the means and standard deviations for the HRV values computed, for the two experimental conditions and during the different phases of the experiment (calibration, divergent thinking, and convergent thinking). We used the recommendations of [35] when reporting the effect size (Cohen's d): 0.25, 0.5, and 0.9 for small, medium and large effects respectively.

We compared the evolution of HRV RMSSDNN values. For the experiment in VR, Wilcoxon tests revealed large significant differences for the RMSSDNN between the calibration and divergent thinking phases (*Z=-4.422, p<.001; Cohen's d=1.26*) and between the calibration and convergent thinking phases (*Z=-4.422, p<.001; Cohen's d=1.27*). For the second experiment (2D sketching), Wilcoxon tests revealed significant differences, medium-sized between the calibration and the divergent thinking phases (*Z=-3.939, p<.001; Cohen's d=.70*), and medium-sized between the divergent and convergent thinking phases (*Z=-3.412, p=.001; Cohen's d=.55*). Taking into account the Bonferroni adjustment there are no significant differences between the calibration and convergent thinking phases (*Z=-2.306, p=.021; Cohen's d=.45*).

Finally, we compared the evolution of the LF bands of HRV during the different phases of the experiment. For the VR experiment, paired T-tests for LF revealed significant differences, large-sized between the calibration and divergent thinking phases (*t=-6.316, p<.001; Cohen's d=1.15*). However, with the adjusted Bonferroni alpha, there are no significant differences between the calibration and convergent thinking phases (*t=-3.505, p=.002; Cohen's d=.66*), and between the divergent and convergent thinking phases (*t=2.095, p=.046; Cohen's d=.40*). For the second experiment (2D sketching), with the Bonferroni adjusted alpha, the Wilcoxon tests revealed no significant differences for the LF values, between the calibration and divergent thinking phases (*Z=-3.099, p=.002; Cohen's d=.68*) and between the calibration and convergent thinking phases (*Z=-2.019, p=.043; Cohen's d=.44*).

B. Galvanic skin response

TABLE II
MEAN VALUES (STANDARD DEVIATIONS) OF THE NORMALIZED LEVEL OF GSR.

	VR 3D Sketching	2D Sketching
Calibration	.018 (.042)	.0664 (.129)
Divergent	.505 (.231)	.493 (.266)
Convergent	.704 (.168)	.658 (.212)

Table II shows all the means and standard deviations for the normalized GSR values computed, for the two experimental conditions and during the different phases of the experiment (calibration, divergent thinking, and convergent thinking). When reporting the effect size (Cohen's d) for GSR data, we consider the standard interpretation: 0.2, 0.5, 0.8, and 1.3 for small, medium, large and very large effects respectively.

We compared the mean values of normalized value of GSR between each phase to compare the evolution of the level of arousal during the experiment. For the first experiment (VR), Wilcoxon tests revealed significant differences between the calibration and divergent thinking phase (*Z=-4.762, p<.001, Cohen's d=2.069*). The tests revealed significant differences as well between the calibration and convergent thinking phases (*Z=-4.782, p<.001, Cohen's d=3.866*). Finally significant differences were also found between the divergent and convergent thinking phases (*Z=-3.774, p<.001, Cohen's d=.894*).

For the second experiment (2D sketching), the Wilcoxon test revealed similar results. Significant differences were found between the calibration and divergent thinking phases (*Z=-4.391, p<.001, Cohen's d=-1.306*). Significant differences were also found between the calibration and convergent thinking phases (*Z=-4.700, p<.001, Cohen's d=-2.012*). Finally significant differences were also found between the divergent and convergent thinking phases (*Z=-2.787, p=.005, Cohen's d=.586*).

VI. DISCUSSION

If the consensus in literature is that arousal and attention are tied with creativity, they can vary greatly depending on the person, the CST used to accompany creativity, and the creative task proposed. Therefore, in our study, we explored how feasible it is to measure these factors through physiological arousal and link them to a specific creative thinking task, regardless of the CST used.

In the case of our experimentation the expectation would be that when performing a creative task, the level of attention and arousal of our participants should significantly rise, due to changes in cognitive load and demanding aspects of the tasks [15]. Our results show significant differences between the calibration phase and the different creative phases. For HRV, the level of RMSSDNN is significantly higher during both creative tasks when compared to the calibration phase for the VR group. For the 2D group, the level of RMSSDNN is significantly higher only in the divergent thinking phase as compared to the calibration phase, and we only find a tendency for the convergent thinking phase. It indicates that our participants were in a state of higher arousal. This is supported by the similar differences observable with the GSR data. Indeed, the level of arousal we computed with the evolution of GSR supports the fact that our participants had a strong physiological arousal response when performing the creative tasks, independently of the medium used. This is consistent with the work of Loudon et al. [15], [16], [27], where participants experience a high level of activation when participating in a creative activity.

Backed up with multiple studies, we hypothesized that it would be possible to discriminate divergent and convergent thinking phases with physiological markers, due to changes in arousal and attention, and independently of the CST used. The analysis of the HRV data collected highlights some differences between the divergent and convergent thinking phases. Indeed, HRV values are overall higher during the divergent thinking phase when compared to the convergent thinking phase. However, contrary to our expectations, the values of LF-HRV did not display significant differences between the convergent and divergent thinking phase. Indeed, it would have made sense, as LF is negatively correlated with level of attention. We expected the participants to be more focused during the convergent thinking phase than the divergent thinking phase, as their attention had to shift from exploring ideas and possibilities to a single idea to refine and enhance [1], [13]. We also observed, for the participants in the interactive whiteboard (2D) group, that RMSSDNN values were significantly lower during the convergent thinking phase when compared to the divergent thinking phase. As stated earlier, RMSSDNN tends to decrease when working memory load increases. This again seems to indicate that the participants experienced enhanced focus during the convergent thinking phase. Regarding the analysis of GSR data collected, we find comparable results. If the participants have a significant activation when performing the tasks, compared to calibration, they are also in a significantly higher level of arousal during the convergent thinking when compared to divergent thinking. The shift in creative activity could lead to a shift in concentration and working memory load, which would result in a rise in arousal. The results we gathered tend to validate our hypothesis, in that divergent and convergent creative tasks, when performed in a classical creative process (get the right ideas then get the idea right), led by specific mental mechanisms, provoke distinct psycho-physiological responses.

Finding comparable physiological responses to the task being performed in both conditions seems to validate that it is tied with the creative process rather than the medium used. To some extent, the differences in physiological responses we found between the divergent and convergent thinking phases suggest that each task induces specific states that can be recognized in real-time. The analysis of the physiological markers tends to indicate a higher level of attention and working memory load during the convergent thinking phase when compared to the divergent thinking phase.

One interesting result observed is the difference between the level of arousal between divergent and convergent thinking. This observation might echo with the work of [36] as well as [37]. Both state that during the design process, the generation of new ideas peaks early and declines over time. This decline of idea generation would logically lead to a drop in physiological arousal over time. In another study, on collaborative brainstorming, [38] reach the same conclusion. They observed a significant drop in idea production after 12 minutes, they named that phenomenon the "death valley" of creativity. Divergent thinking for the VR experiment lasted on average 12 minutes (733.03s, SD=252.561s) and for the 2D experiment 12.7 minutes (765.30s, SD=326.459s). This result opens some interesting perspectives, indeed, if our analysis of physiological data potentially allows for the detection of a specific creative thinking mental process, it could also help detect and prevent this "death valley". Are the designers reaching the end of their creative drive, the "death valley"? The ability to answer these questions in real-time could allow the facilitator to improve creative sessions [39]. Additionally, observable differences between divergent and convergent thinking (when performed in the classical creative process we presented) may help the facilitator verify if the participants successfully entered the next "phase" of their creative process and not stagnate on divergent thinking [2], [3], [36]. Moreover, with the flexibility offered by VR, it could be possible to alter the virtual environment in real time, in response to the state of the designers, to unlock specific part of the creative process and better accompany the designers.

VII. LIMITATIONS

If we tried to have as thorough analyses as possible with our physiological data, interpersonal differences are complicated to tackle. It could have been beneficial to train and use machine learning algorithms to highlight specific differences and classify emotions associated with creative thinking and clearly characterize the state of the participants. The lack of data and annotators limited our ability to conduct such a large study.

While it could be argued that both mediums offer too different experiences, we aimed to propose as comparable experimental conditions as possible. It is questionable whether the participants in VR, who have virtual representations of the warehouse and the crankset, can be compared to the participants using the interactive whiteboard, who are in a regular room but have a real crankset next to them to take inspiration from. However, using VR in an incomplete state, without a contextualized 3D environment, defeat the purpose of the technology and does not represent how it will be used in real conditions. Nonetheless, both groups were free to move, explore, and behave as they wished during the experiments (even if VR encourages spatial exploration more, due to the embodied nature of its interactions).

Finally, in our experiments, we decided to compare two separate groups of participants over two distinct CSTs. The difficulty in proposing a within-participants design resides in the ability to propose two creativity scenarios that could be comparable to measure the production of ideas. The creativity tasks are unique, and we wanted to test our experiment on users who were naive to the scenario. While we chose a between-participants design, we tried to recruit a significant number of participants to have enough power for our analysis.

VIII. CONCLUSION AND FUTURE WORK

This article presents a user study we conducted on physiological responses as markers of creative thinking phases over different sketching CSTs (3D immersive VR and 2D interactive whiteboard). Our goal was to examine physiological arousal as a marker of divergent and convergent thinking, during a classical creative session, independently of the sketching medium used. We hypothesized that there were clear differences between divergent and convergent thinking in terms of physiological arousal, due to changes in attention and working memory load.

We were able to detect significant increase in GSR and HRV values, indicating heightened physiological arousal when the participants performed the creative tasks. We also observed significant differences in GSR values between divergent and convergent thinking, which were comparable over the two CST we used.

We found some interesting results regarding the GSR and HRV responses during the divergent thinking phase. Indeed, the level of physiological arousal is higher during the convergent thinking phase than the divergent thinking phase. Over time, when performing a divergent thinking task, the participants could experience a natural decline in idea generation, leading to a decrease in physiological arousal. More work is to be done on the analysis of the evolution of arousal over the divergent thinking task especially with pattern matching techniques to identify recurring behaviors or the computation of more detailed features of GSR (e.g. phasic and tonic components).

For the future of our work, we want to explore more deeply the relationship between arousal and creative performance. The literature seems to indicate that VR can boost creativity. Is it linked with its highly arousing nature, provoked by novelty and immersion? With our results, we can begin to detect creative thinking phases based on arousal patterns. The next step would be to exploit these data directly to enhance creativity. Indeed, if we are able to detect a specific creative state or changes in arousal, we could adapt the virtual environment in real time to support and enhance the designers' creative process, leveraging VR's unique capabilities, to foster creativity. We aim to propose a theoretical model that would establish connections between arousal, creative performance, and the user's experience during a creative session using a CST.

ETHICAL IMPACT STATEMENT

At the time of our study we consulted with our institution and it was considered that we did not need to validate that study through an ethical committee. Moreover, we followed the recommendations formulated by [40], especially the principles of non-maleficence and informed consent.Data has been anonymized and availability is conditioned to reasonable uses. We didn't identify negative societal impact linked with our study, as our data is tied to a very specific context and are not collected to contribute to deep emotional analysis.

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