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CREATIVE THINKING: IMMERSIVE, INTERACTIVE, AND MULTISENSORY EXPERIENCES

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Abstract. Virtual reality is a technology widely employed in cognitive science, aimed at studying human behavior and cognition. In recent years, virtual environments have been applied to investigate human creative process, focusing on divergent thinking. Along this line of research, our study addresses the immersive, interactive, and multisensory aspects of virtual reality technologies to enhance individuals' creative thinking. We tested a sample of N = 60 participants, using positive (N = 20), negative (N = 20), and neutral (N = 20) auditory stimulation within an interactive virtual environment, in order to test possible change in divergent and associative thinking. Our findings provide a first piece of evidence that immersive, interactive, and multisensory experiences enhance human creative thinking, particularly using positive auditory stimulations.

Keywords: creativity, divergent thinking, multisensory experience, rebus puzzle task, remote associates test, virtual reality.

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1. Introduction

Virtual reality is an immersive technology that promises important advantages in the study of human cognition (Foreman, 2009). In recent years, virtual reality has been used to study human creativity with the aim of developing creative thinking, supporting in creative tasks, and engaging people in novel experiences (Burkhardt & Lubart, 2010).

Virtual reality can be considered a valid technological tool aimed at improving the study of creativity as it shows various advantages on respect to more traditional technologies, among these the possibility for users of: 1) changing the frame of the environment; 2) feeling present in a virtual world; 3) being immersed; 4) combining different stimulations, *i.e.*, linked to multimodality; 5) acting and interacting in a simulated world – thus not just with familiar objects but also with novel objects, with which individuals cannot have had previous experience (Alahuhta et al., 2014).

In this sense, previous studies have used virtual environments in order to foster human creativity in collaborative brainstorming activities (Bonnardel & Pichot, 2020; Forens et al., 2015) or in music composition (Men & Bryan-Kinns, 2018, 2019), as well as in composition of three-dimensional objects (Obeid & Demirkan, 2023) or in painting activities (Joy Gerry, 2017).

For example, in the musical domain, Men and Bryan-Kinns (2019) used a virtual reality headset in a collaborative creativity task, allowing participants to cooperate in creating a short loop of music by manipulating the virtual interface. In the domain of three-dimensional objects' composition, Obeid and Demirkan (2023) tested students' creative performance through an immersive environment where participants, by applying basic design principles, could create different complex novel patterns using familiar three-dimensional objects such as sparihere, cylinder, prism, and pyramid.

Regardless of the specific kind of task to be performed, the experiences in virtual reality itself seems to be able to elicit human creative process, thanks to the experienced arousal of emotions. Among the different empirical evidence, we mention the one by some authors (Agnoli et al., 2021): they tested the influence of four virtual environments on users' creative performance, by means of different tasks addressing divergent thinking. Their results show a significant influence of the experience in virtual environments not just on a cognitive level, that is in the originality of produced ideas, but also on an emotional level, as shown by the emerging of positive emotions.

Other studies have focused on the awe-effect often elicited by specific virtual environments. The awe-effect can be conceived as a complex emotion composed by both sense of vastness and need for accommodation (Keltner & Haidt, 2003). The awe-effect has been found using natural environments (van Cappellen & Saroglou, 2012), but also human artifacts, *e.g.*, cathedrals (Keltner & Haidt, 2003), historical figures as well as scientific discoveries (Chirico & Yaden, 2018). For examples, the studies by some authors (Pizzolante et al., 2023) and by other researchers (Chirico et al., 2018; Chirico & Gaggioli, 2023) demonstrate that awe experiences in virtual environments can elicit the human creative process, understood as divergent thinking.

In the reviewed literature, there is a lack of work using virtual environments, exploited both in the feature of immersiveness, interactivity, and multisensoriality, to investigate whether the quality of conveyed emotions (positive, negative, or neutral) can influence creative thinking. The present work aims to fill this gap. We addressed whether immersive virtual environments equipped with interaction and multisensoriality can improve human creative thinking when conveying emotions by means of positive, negative, or negative auditory stimulations. To the immersion, conceived as the state of flow of the creative process in which the user is totally immersed in a specific task (consistently with Csikszentmihalyi, 1997)), we added both the interaction within the virtual environments, to stimulate the imagination of users, and the multisensoriality: we delivered participants with not just visual stimuli but also with (emotionally connotated) auditory stimulation (see Figure 1), in order to address possible effects of a different range of emotions on human creativity. Although is hard to manipulate immersion as intended by Csikszentmihalyi (*i.e.*, a psychological state in which a person is completely involved and absorbed in a specific task) in our protocol we tried to operationalize exploiting virtual environments: living an experience in virtual reality produces a total immersion of the user by completely isolating him/her from the surrounding world, *i.e.*, yielding a physical and psychological state that closely approximates the definition by Csikszentmihalyi.

Participants, upon immersed in the virtual reality environment, were instructed to actively interact with three-dimensional solids in order to create novel objects. The available solids could be stationary or self-moving; in case of moving objects, they could follow or not the laws of physics. Thus, while some solids remained stationary, others moved upwards and could also collide with others. This allowed users to unleash their imagination (and creativity) without the physical constraints of the real world, possibly evoking novel problem solving strategies. As anticipated, we did not neglect the multisensory component: in addition to visual stimuli, acoustic stimuli were delivered – that may or may not convey emotions.

In our experimental paradigm, the choice to work on the quality of emotions stems from an analysis of previous empirical evidence, particularly of studies showing that emotional states can elicit human creative process (George & Zhou, 2007; Agnoli et al., 2019). As a matter of fact, creativity seems to be linked to the reward system (Wright & Panksepp, 2012) which drives exploration, search for information and desire for new experiences.

Once the paradigm is defined, the serious issue all creativity studies face is how to measure it. In keeping with major studies in this area (Ferraro III, 2015; Chirico et al., 2018; Pizzolante et al., 2023), to evaluate the creative thinking we used divergent thinking' tests administered before and after virtual reality experience.

In a nutshell, the novelties of our study are mainly four:

1. We investigate the influence of positive as well as negative emotions in stimulating participants' creativity, intended as divergent thinking;
2. We use acoustic (validated) stimuli to convey (positive and negative) emotions, rather than traditional visual stimulation; to these two conditions we added a neutral one, with no stimuli (white noise was excluded as control condition because it is typically associated with specific contexts and/or actions);
3. Unlike other studies where virtual environments are applied, in our work we act not only on multisensoriality and immersivity, but also on participants' interaction within the environment (see Figure 1). While the first two components of virtual reality are often investigated in the literature, there are few empirical works where participants

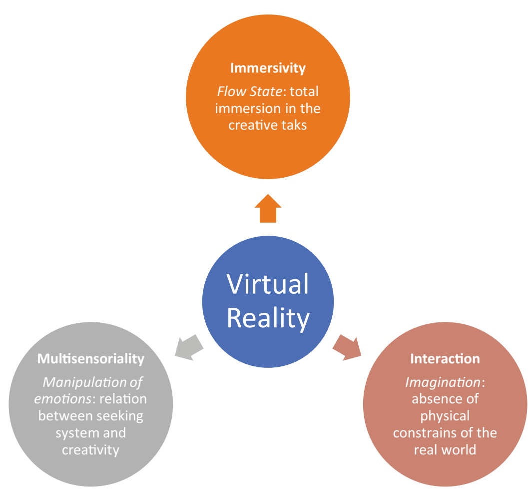


Figure 1. A schematic representation of the three main characters of our virtual reality system used to enhance creativity in healthy participants, related to the immersivity (flow state of creative process), interaction (imagination), and multisensoriality (manipulation of emotions) (source: created by authors)

are actually allowed to interact in an ecological way in the environment (*i.e.*, using their hands without joystick) and possibly modify it to their liking (the choice to convey emotions through acoustic, and not visual, stimuli allows indeed to avoid intervening on the visual scenario, "modifiable" only by users: experimenters intervened only on the auditory scenario, not changeable by participants);

4. The virtual environment used is original: a completely novel scenario for participants, with which they could not have had previous experience.

The hypotheses of our pioneering study are twofold:

1. An effective virtual reality experience, thus not only multisensory and immersive, but also allowing for interaction, produces significant effects in improving creativity, intended (and operationalized) as divergent thinking;
2. Emotional stimulation (conveyed through auditory stimuli) further enhances participants' creativity.

2. Method and materials

2.1. Participants

In our study we tested a total of N = 60 university students, divided into three groups of N = 20 participants, balanced for age, gender, and nationality of participants. Our three groups were defined by the sensorial and emotional nature of the administered task.

The first group (positive condition) is composed of 7 males and 13 females with an average age of 21 standard deviation 3.44. The second group (negative condition) is composed of 6 males and 14 females with an average age of 22 standard deviation 4.96. The third group (control condition, without auditory stimuli) is composed of 10 males and 10 females with an average age of 21 standard deviation 1.00. No gratuity was given to the participants.

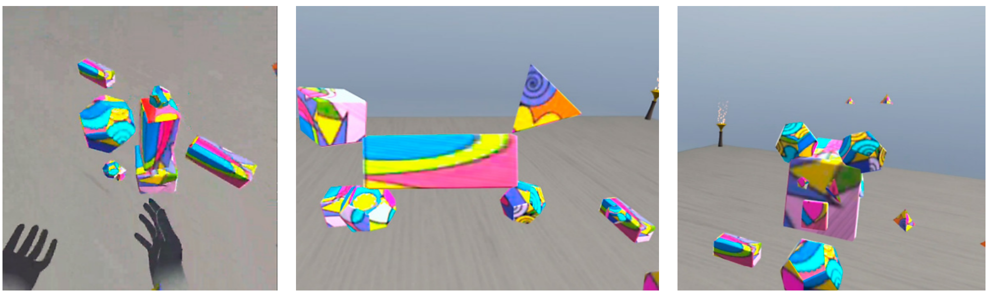
All the participants gave their informed consent to participate in the research. The study was approved by the local ethics committee of the University of Bologna, Italy (protocol no. 0152607).

2.2. Materials

To be sure that the auditory stimuli were effective in eliciting positive and negative emotions, we used acoustic stimuli previously validated by some authors (Koelsch et al., 2013), that is Johann Sebastian Bach's orchestral suite no. 4 in D major, BWV 1069, in the pleasant and unpleasant version. In this functional magnetic resonance imaging (fMRI) study, the unpleasant stimulus was constructed by altering the amplitude of the symphony's sound to evoke negative emotions in users. Using fMRI they showed the involvement of emotion-related brain regions, such as the amygdala, in response to both pleasant and unpleasant auditory stimuli (Koelsch et al., 2013). For the control condition the best choice would have been to use white noises (*e.g.*, hair dryer, air conditioner), but they would have introduced bias as they are typically associated to specific contexts (*e.g.*, domestic) and they usually evoke actions (*e.g.*, drying one's hair): this would have influenced subjects' task in the virtual environments, making this condition no longer comparable to the others. In the control condition, no acoustic stimulus was thereby administered.

2.3. Virtual reality environment

In our experimental research we used an immersive and multisensory virtual environment, in which participants can interact with three-dimensional objects in order to build a creative artefact, *c.f.* Figure 2. Our virtual reality environment consists of a simple room, in which there is just a panel (the floor on which users can walk), four decorative torches in the corner, and some multicolour geometric solids, *i.e.*, cubes, spheres, and parallelepipeds. For our virtual environment we used *Unity* (game engine) three-dimensional as software and *Quest 2* as helmet of virtual reality. Three-dimensional objects present specific characteristics as "graspability", that allows users to interact and directly manipulate the objects; "changeability", that allows users to change the dimensions of the objects; only some of the three-dimensional objects had the characteristic of "alternative physics", since in their movements they do not adhere to typical laws of physics.



a) b) c)

Figure 2. Our virtual environment, in which healthy participants can interact with three-dimensional solids using their personal hands (a) and the creative artworks made by the users, *e.g.*, "cat" (b) and "piglet" (c) (source: created by authors)

2.4. Selected test to investigate creativity

To test the human creativity, we used the Kaufman domains of creativity scale (K-DOCS) (Kaufman, 2012) that is a self-report questionnaire composed by 50 items on a 5-point Likert scale related to the five dimension of creativity: self-everyday creativity, scholarly creativity, performance creativity, mechanical/scientific creativity, and artistic creativity.

About the divergent thinking, we used the Italian version of remote associates test (RAT) and the rebus puzzle test (Salvi et al., 2016) that were administered before and after the virtual reality experience.

Rebus puzzle test (Salvi et al., 2016) is based on 20 categories that can be divided into 9 tasks, that are: 1) verbal interpretation; 2) spatial relationship; 3) mixed word and image; 4) mixed number, word, and symbol; 5) fragmentation; 6) repetition; 7) word into word; 8) anagram; and 9) negation. We selected a total of 24 rebus, that were administered 12 pre-virtual reality and 12 post-virtual reality counterbalanced. For each category we selected 4 rebuses (2 pre-virtual reality and 2 post-virtual reality) related to the degree of difficulty that is "easy" and "hard" based on the percentage of error validated by some authors (Salvi et al., 2016).

Table 1. The rebus puzzle stimuli that authors used in their experimental study. They are divided in 6 categories (4 rebus for each category), timing (pre-virtual reality and post-virtual reality experiences, counterbalanced), and degree of difficulty (easy versus hard) (source: created by authors)

Category	Difficulty (based on percentage, %, error)	Timing (counterbalanced)
Verbal interpretation	Easy (6.9)	Pre-virtual reality
Verbal interpretation	Hard (22.2)	Pre-virtual reality
Verbal interpretation	Easy (5)	Post-virtual reality
Verbal interpretation	Hard (28)	Post-virtual reality
Spatial relationship	Easy (6.4)	Pre-virtual reality
Spatial relationship	Hard (34.5)	Pre-virtual reality
Spatial relationship	Easy (5.2)	Post-virtual reality
Spatial relationship	Hard (32.1)	Post-virtual reality
Mixed word and image	Easy (7.8)	Pre-virtual reality
Mixed word and image	Hard (22)	Pre-virtual reality
Mixed word and image	Easy (15.4)	Post-virtual reality
Mixed word and image	Hard (22)	Post-virtual reality
Mixed number, word, and symbol	Easy (10.3)	Pre-virtual reality
Mixed number, word, and symbol	Hard (17.8)	Post-virtual reality
Mixed number, word, and symbol	Easy (13)	Post-virtual reality
Mixed number, word, and symbol	Hard (20.4)	Pre-virtual reality
Word into word	Easy (0)	Pre-virtual reality
Word into word	Hard (23.7)	Post-virtual reality
Word into word	Easy (1.8)	Post-virtual reality
Word into word	Hard (20.4)	Pre-virtual reality
Negation	Easy (13)	Post-virtual reality
Negation	Hard (28)	Post-virtual reality
Negation	Easy (6.9)	Post-virtual reality
Negation	Hard (17.6)	Post-virtual reality

We excluded some categories, like fragmentation word (only 2 items), anagram (just 1 item), repetition of words for number (no balanced percentage of error). Table 1 shows the stimuli that we used and their degree of difficulty.

RAT (Salvi et al., 2016) is divided into 4 categories that are: 1) remote association; 2) same domain; 3) additional letter; and 4) idiomatic expression. We selected a total of 12 stimuli, administered 6 pre-virtual reality and 6 post-virtual reality counterbalanced. For each category we selected 4 tasks (2 pre-virtual reality and 2 post-virtual reality) related to the degree of difficulty that is "easy" and "hard" based on the percentage of error validated by some authors (Salvi et al., 2016). We excluded the additional letter category, because there are only 3 items. Table 2 shows the stimuli that we used and their difficulty.

Finally, in order to record the degree of immersivity and presence in the virtual environment we used the presence questionnaire (Witmer et al., 2005) which is composed of 24 items

Table 2. The remote associates test stimuli that authors used in their experimental study. They are divided in 3 categories (4 rebus for each category), timing (pre-virtual reality and post-virtual reality experiences, counterbalanced), and degree of difficulty (easy *versus* hard) (source: created by authors)

Category	Difficulty (based on percentage, %, error)	Timing (counterbalanced)
Remote association	Easy (5.3)	Pre-virtual reality
Remote association	Hard (22.3)	Pre-virtual reality
Remote association	Easy (5.7)	Post-virtual reality
Remote association	Hard (22.4)	Post-virtual reality
Same domain	Easy (3.7)	Pre-virtual reality
Same domain	Hard (18.4)	Pre-virtual reality
Same domain	Easy (3.4)	Post-virtual reality
Same domain	Hard (24.3)	Post-virtual reality
Idiomatic expression	Easy (7.6)	Pre-virtual reality
Idiomatic expression	Hard (22.8)	Pre-virtual reality
Idiomatic expression	Easy (7.4)	Post-virtual reality
Idiomatic expression	Hard (23)	Post-virtual reality

on a 7-point Likert scale related to the degree of perceived immersion. It investigates different aspects of the virtual environment, like: realism, possibility to act, quality of interface, possibility to examine, self-evaluation of performance, sound, haptic, and the total score.

2.5. Procedure

First, we recorded demographic variables such as age, gender, occupation and we asked the user to complete the self-report questionnaires about creativity (K-DOCS). Then we administered the RAT and rebus puzzle test. Here we give to the user 0.25 seconds for each item, we recorded the reaction time and the number of correct and incorrect answers.

Participants were instructed to interact for five minutes with the three-dimensional solids in the virtual reality environment in order to a build a creative artwork. Our three-dimensional objects are programmed in order to respect and/or not the low of gravity. This allows us to give the participants the possibility to use the virtual environment with problem solving strategies that cannot be used in the real world for practical reasons. The users stay in the virtual environment for 5 minutes, only the experimental groups are submitted to the emotional auditory stimulation. The positive (pleasant) or negative (unpleasant) stimulus occurs every 30 seconds for the duration of 10 seconds, a total of 8 times. At the beginning, for 10 seconds the user can look at the virtual environment, then we divided the time in 80 seconds for the incipit, 130 seconds for the core of the experiment and 80 seconds for the refinement. These temporal windows were created according to the creative process, which consists of different phases, from the identification of a task to the assessment of a generated idea (Graessler & Taplick, 2019).

The stimulation occurs with 2 stimuli in the incipit and refinement phases and 4 stimuli in the core phase (Figure 3). We recorded the interaction of the users with the virtual objects for the entire duration of the experiment.

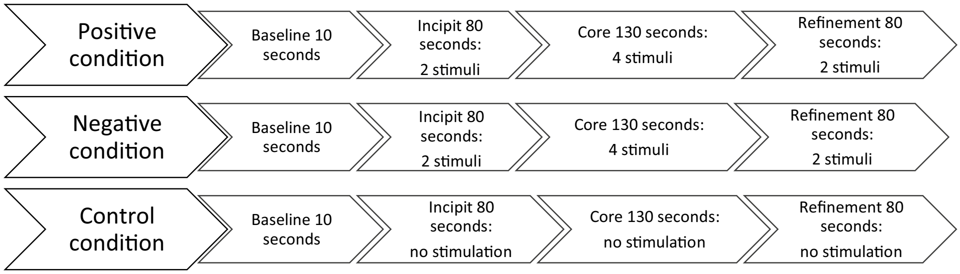


Figure 3. Flowchart of the stimulation timing during the creation task. Authors used a total of 8 stimuli (2 in the incipit phase, 4 in the core phase, and 2 in the refinement phase), each stimulus is administered for 10 seconds every 30 seconds (source: created by authors)

At the end of the virtual reality experience, participants were invited to solve the RAT and rebus puzzle test. Here we used different items, balanced for the degree of difficulty, giving to the user 0.25 seconds for each item. We recorded the reaction time and the number of correct and incorrect answers.

Last, participants were invited to complete the presence questionnaire test, in order to evaluate the degree of immersivity and presence about the virtual reality environment.

3. Data analysis

Based on Shapiro–Wilk test that shows a normal distribution of our data ($p > 0.05$) we used parametric analysis. Firstly, we calculated the percentage of the kinds of emotions evocated by the auditory stimulation (section 3.1.); then we performed Student's t-test analysis to verify the sense of presence in our three conditions (section 3.2.). Concerning the divergent thinking, more crucial for our hypothesis, we used Pearson correlation coefficient between the valence of auditory stimuli and the scores of creativity test (section 3.3.); also, we performed Student's t-test analysis on RAT and rebus puzzle test scores pre-virtual reality and post-virtual reality experience (section 3.4.). Finally, about user's interactions, we used Student's t-test analysis to calculate the difference in terms of number of interactions among the three conditions, for the incipit, core and refinement phases; also, Pearson correlation coefficient between the total number of interaction and creativity traits (section 3.5.).

3.1. Emotional check

We used positive and negative auditory stimulation in order to evoke the emotions of the users. To be sure that our auditory stimuli were effective in eliciting specific emotions in the participants, we did an emotional check after the virtual reality experience. Specifically, we asked the user to explain his/her feeling based on the Ekman's (2000) emotion classification (happiness, sadness, surprise, disgust, fear, and anger) in relation to the auditory stimuli in the virtual world. Our results show that in the positive condition participants express positive emotions (45% happiness, 50% surprise, and 1% nothing) and in the negative condition participants express principally negative emotions (25% anger, 20% disgust, 30% fear, and 25% nothing) (Figure 4).

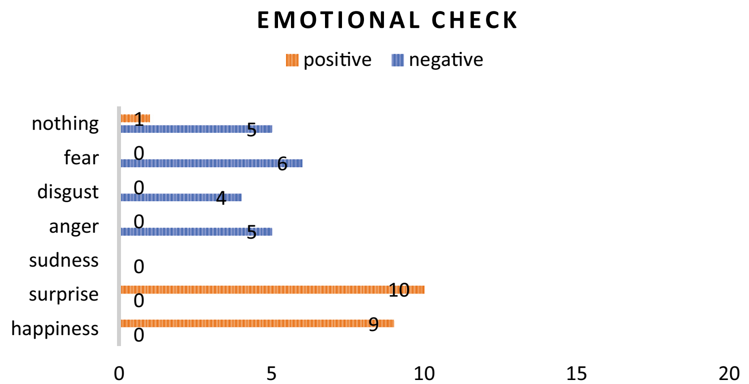


Figure 4. The distribution of Paul Ekman's (2000) emotions of the users in the positive (yellow) and negative (blue) condition (source: created by authors)

In summary, our check showed that the auditory stimuli elicit a range of different emotions, or even no emotion at all, with comparable percentages (*i.e.*, anger, disgust, fear, nothing).

3.2. Sense of presence and creativity

The sense of presence is higher in the negative and positive conditions rather than in the neutral condition (Student's *t*-test: positive *versus* neutral < 0.001, negative *versus* neutral <0.001). Figure 5 shows the mean of the total score related in our three conditions.

This result indicates that the auditory stimulation (positive or negative) has an influence on the sense of presence perceived by the users. During positive stimulation, participants report a total score in the presence questionnaire test of M = 122.45; in the negative stimulation of M = 124.55 and in the neutral condition of M = 103.85.

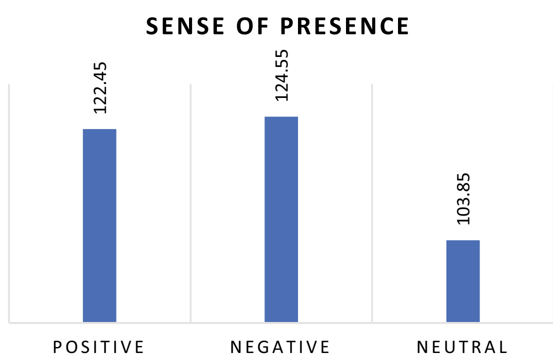


Figure 5. Total score of the presence questionnaire of participants, per each condition (positive, negative, and neutral) (source: created by authors)

3.3. Valence (positive *versus* negative) of sound and creativity traits

Pearson correlation coefficient shows that in the positive condition there is a positive relation between the subscale related to the valence (positive *versus* negative) of sound and the performance creativity (subscale of K-DOCS test) (r = 0.448, p = 0.049), it means that people with high levels of performance creativity are more able to perceive the valence of sound in the positive stimulation. This result is not significant in the negative condition (r = 0.223, p = 0.344). Here there is a significant positive relation between self-everyday creativity (subscale of K-DOCS test) and the subscale related to the possibility to act (subscale of presence questionnaire test) (r = 0.652, p = 0.002): this result suggests that people with high levels of self-everyday creativity are more focused on the possibility to act within the virtual world. Taking into account also the results of our check on the "actually evoked emotions" (see section 3.1.), it seems that the negative (actually "non-positive") sounds are more powerful of positive ones in evoking the possibility to act, because there are no significant results in the positive condition concerning the possibility to act and self-everyday creativity trait (r = 0.316, p = 0.174).

In summary, these correlations show that there is a significant link between the personal creativity traits of the users (measured through K-DOCS test) and the auditory stimulation (positive *versus* negative) used in the virtual reality environment.

3.4. Divergent thinking

Our findings show that there is an increase in the divergent thinking, investigated through RAT and rebus puzzle test pre-virtual reality and post-virtual reality experience, in all the conditions (Figure 6).

In the positive condition, Student's t-test analysis shows that there is a significant difference in the RAT (p = 0.043) and rebus puzzle test (p = 0.003) pre-virtual reality and post-virtual reality experience. In the negative condition there is a significant difference in the RAT (p = 0.038) and not in the rebus puzzle test (p = 0.202). While in the control condition there is a moderate significant difference in the rebus puzzle test (p = 0.049) and not in the

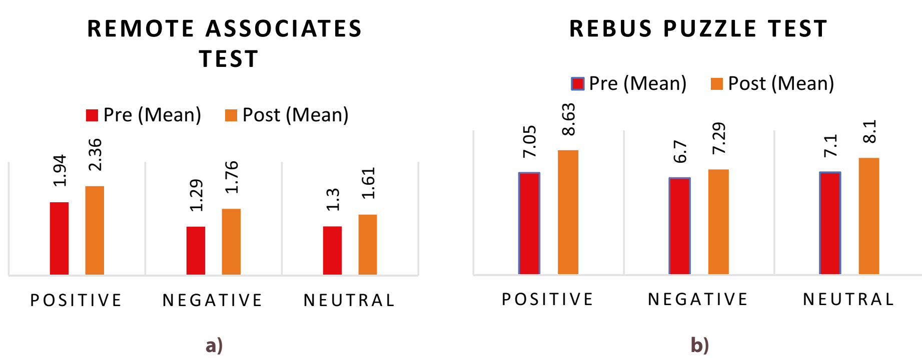


Figure 6. The mean of correct answers in the remote associates test (a) and rebus puzzle test (b) before and after the virtual reality experience. This chart shows that there is an increase in all the conditions in the divergent thinking of users after the virtual reality experience (source: created by authors)

RAT (p = 0.092). There are no significant differences in the reaction time in all the conditions (positive RAT: p = 0.137, rebus puzzle test: p = 0.157; negative RAT: p = 0.26, rebus puzzle test: p = 0.48; neutral RAT: p = 0.07, rebus puzzle test: p = 0.15).

These results show that a multisensory, interactive and immersive experience enhances the creative thinking of the users, especially using positive auditory stimuli. Here there is an increase both in the associative thinking and in the divergent thinking.

3.5. Interactions in the virtual reality environment

During the creative task in virtual reality, we recorded the number of interactions considering the total timing divided into three steps that are incipit, core, and refinement. Interactions represent the number of times the user interacts with a three-dimensional object, such as changing its size or positioning it in a specific place. These interactions were automatically detected through the *Unity* (game engine), using a script specifically developed to contain the interactions between the subject and the object.

Student's t-test analysis in the incipit phase shows a significant difference in the number of interactions between positive *versus* negative condition (p = 0.038) and between negative and neutral condition (p = 0.007). Here there are higher levels of interaction in the positive (N = 91) and neutral (N = 97) rather than negative (N = 73) condition.

In the core phase, there is a significant difference in the positive condition *versus* negative (p = 0.035) and neutral (p = 0.032). The mean of interaction is N = 202 in positive stimulation, N = 162 in negative stimulation, and N = 164 in the neutral condition.

In the refinement phase, there is a significant difference in the positive *versus* neutral condition (p = 0.003), with a mean of interaction of N = 115 in the positive condition and N = 95 in the negative (N = 59 in the neutral one) (Figure 7 and Table 3).

It is clear from the analyses that when participants listen to positive-pleasant acoustic stimuli they interact more with solids in the virtual environment than under conditions in which non-positive stimuli are administered. Thus, emotions evoked by our positive stimuli

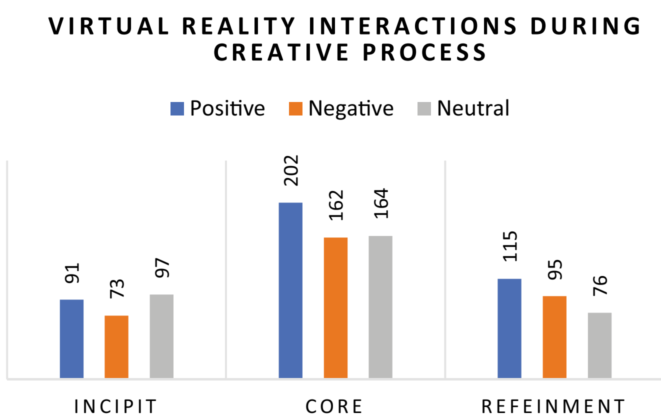


Figure 7. Virtual reality interactions during creative process (incipit, core, and refinement) in positive, negative, and neutral conditions (source: created by authors)

Table 3. The Student's t-test analysis and the mean of interactions among all the conditions (source: created by authors)

Interactions	Incipit	Core	Refinement	Conditions	Incipit	Core	Refinement
Positive *versus* negative	0.038*	0.035*	0.135	Positive	91	202	115
Negative *versus* neutral	0.007*	0.458	0.158	Negative	73	162	95
Positive *versus* neutral	0.274	0.032*	0.003*	Neutral	97	164	76

Note: * indicates significant results.

(happiness and surprise) enhance interaction compared to those evoked by our negative stimuli (anger, disgust, fear, nothing), consistently with the literature (Pallavicini et al., 2018). Interactions are also significantly lower in the condition of no acoustic stimulation, but this result could be explained by the lower degree of multisensoriality of the virtual environment.

Pearson correlation coefficient shows that in the positive condition there is a significant relationship between the total number of interactions within the virtual world and both self-everyday creativity (r = 0. 575, p = 0.008) and artistic creativity (r = 0.485, p = 0.030) of the users, evaluated through K-DOCS test.

These results show that the auditory stimulation (positive, negative, or neutral) has an influence on the objects interactions within the virtual environment. Specifically, our findings show that there is an increase in the number of interactions in the positive condition compared to negative and neutral conditions.

4. Conclusions and discussion

Based on previous studies (Chirico et al., 2018; Agnoli et al., 2021; Pizzolante et al., 2023) about the use of virtual reality technologies in the field of creativity, in our study we used an immersive virtual environment equipped with interaction and multisensoriality in order to elicit the creative thinking of the human subjects. While interaction allows to stimulate the imagination of users, multisensoriality (visual and auditory) allows to elicit human emotions.

We investigated the power of immersive, interactive and multi-sensory experiences using three conditions related to the auditory stimulation. We tested the positive condition with auditory stimuli able to elicit positive emotions; the negative condition with auditory stimuli able to elicit negative emotions; and the neutral condition without auditory stimuli.

Our findings show that:

1) In the positive condition there is a good level of the sense of presence experienced by the users within the virtual environment. Here, the creativity of users' performance increased with the increase in the perception of sound. It means that people with higher creativity scores, measured before the experiment, tend to perceive the valence of sound more distinctly in the positive condition. Then, during the positive stimulation there is an increase in the total number of interactions with the virtual objects in the three steps of creation related to the incipit, core and refinement phases. Our findings

show that as self-everyday creativity and artistic creativity increase the number of interactions increases. Our results show also that, after the positive stimulation in virtual environments, divergent and associative thinking significantly increase;

2) In the negative condition there is a higher level of presence and immersivity. Here, self-everyday creativity increases as increases the possibility to act within the virtual environment, while performance creativity is not significantly correlated with the perception of sound. This allows us to hypnotize that the negative auditory stimulation brings people to be more centered on the action than on the sound. In relation to divergent thinking, after the virtual reality experience, the negative stimulation shows a significant increase just in the associative thinking;
3) In the neutral condition, in which there is not an auditory stimulation, our results show a decrease of the sense of presence and a decrease of the total number of interactions, especially in the refinement phase. The lack of auditory stimulation seems to act negatively on the divergent creativity, as a matter of fact our results show a moderate significant increase just in the divergent thinking after the virtual reality experience.

As far as our hypotheses are concerned:

1) The first hypothesis has been verified. Indeed, our results confirm that virtual reality environments can enhance human creative process, as shown by some authors (Agnoli et al., 2021; Chirico et al., 2018; Pizzolante et al., 2023). The addition of interaction and multisensoriality appears to have a significant impact on the human creative process, especially in the positive condition. Moderate changes are also found in negative and neutral stimulation;
2) The second hypothesis was partially confirmed due to the limits of the present work, basically two, that is:
   a) in the neutral condition we could not use white noises (because they are typically associated with specific contexts and/or actions), but the absence of stimulation. The absence of auditory stimulation, however, necessarily reduced multisensory stimulation: in fact, in the neutral condition we found less sense of presence of the participants;
   b) the stimuli used for the negative valence condition, although selected from a dataset of previous work (Koelsch et al., 2013) were not found to be fully adequate: in fact, our check showed that those sounds elicit a range of different emotions, or even no emotion at all, with comparable percentages (*i.e.*, anger, disgust, fear, nothing), so they would more correctly be labelled as non-positive.

To summarize, while accounting for the reported limitations, our study highlights the potential of virtual reality to enhance human creativity. This suggests that virtual reality can be effectively applied to create immersive and multisensory experiences, giving users the opportunity to experience situations, environments, sounds and interactions that would otherwise be inaccessible. Based on this, virtual reality tools able to enhance the creative thinking could be integrated into educational context, considering that creative thinking can enhance various human skills, as recently demonstrated also by the Organisation for Economic Co-operation and Development Programme for International Student Assessment ([OECD], 2024).

5. Limitations

Although the results of this challenging study are novel and encouraging, future developments of this work need to introduce a new neutral condition, with white noises that are not associated (or weakly associated) with specific contexts/actions. Furthermore, future studies need to consider the use of different auditory stimuli, thus selecting sounds that are clearly polarized in valence as positive (happiness) and negative (fear).

6. Note

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