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Multisensory objects' role on creativity

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ABSTRACT

In this research, we investigated the role of multisensorial manipulation on creativity, and the influence of inspirational objects on creative outcomes. Object manipulation may support embodied cognition during a generative creative phase (emergence of motor, spatial, emotional ideas, etc.) then exploratory phase (creative fixation, development of a functional creation, etc.). Our protocol involved 136 engineering students divided into 34 groups which were provided with inspirational cubes illustrating manufacturing inventive principles or basic volumes from the Creative Mental Synthesis Task. They could manipulate these objects either in a visuo-haptic condition, or in a visuo-imaginative condition. Our results highlighted a main effect of manipulation, showing that visual-haptic condition led to higher creativity than visual-imaginative condition. We also observed several effects in favor of inspirational cubes with regard to basic volumes: significantly higher creativity, more subjective and inter-subjective facilitation behaviors, more cognitive and emotional operations. Participants also showed at an individual level a better mobilization of the multisensorial senses. Creative thinking may be stimulated when an active manipulation phase is set up before the creative production. This could contribute to improving practice for engineers, particularly for using additive manufacturing and/or during their training at school.

Multisensory objects' role on creativity

When an individual appropriates an object, he or she does so first with the visual sense (Hatwell & Cazals, 1988). This 'visual capture' provides the available information but can deprive him or her of the functionality of other senses (Lacey & Sathian, 2014; Saradjan, 2015). From generation to generation, we have seen an increase in occipito-temporal and prefrontal cortex as well as an increase in hemispheric speciation allowing human species to develop their higher cognitive functions and social life (Borst et al., 2006; Changeux, 2002; Changeux & Chavaillon, 1995). In particular, mental imagery may be closely linked to creativity. Mental imagery refers to representations accompanying the experience of sensory information with external stimulus. Internal associations and external events can trigger a mental image, with all the senses. An individual performing a creative task mobilizes these functions, which themselves require external factors to develop. Thus, interaction with others, objects, and with material promotes situated cognition, as well as the sensory and motor systems (Lang et al., 2021). The main goal of our research was to investigate the role of multisensorial manipulation on creativity, and the influence of objects that are manipulated as inspirational sources on mental imagery and creative process. These issues were studied in the context of engineering creativity as it is important and necessary to industrial innovation (Baharom et al., 2013; Suram & Bryden, 2015; Vuletic et al., 2018). This paper is organized as follows. In section 2 we present the theoretical background about creativity and mental processing in Creative Mental Synthesis Task. In section 3 we present the methods and results from an experimental study. Finally, a discussion section highlights the most important outcomes of our research.

Creativity is often illustrated as the ability to represent and create objects from different stimuli (Amabile, 1996). It may also be linked to a particular - intrinsic - motivation pushing human beings to create with their fellow human beings (Forgerad & Mecklenburg, 2013). Human sensory-motor development unfolds throughout life with significant

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invariances derived from information available in the environment, notably *via* visual and haptic modalities (Lederman & Klatzky, 1987). Experimental research in this area encouraged individuals to assemble items through mental images or physical objects to create new solutions (Bouchard & Drauden, 1976; Anderson & Helstrup, 1993; Cseh et al., 2016; Finke, 1990; Finke et al., 1992; Finke et al., 1989; Hubbard, 2010; Kokotovich & Purcell, 2000; Palmiero & Piccardi, 2020; Tam et al., 2016; Ward & Sifonis, 1997; Ward et al., 2002).

Research showed that mental imagery may contribute to creativity (Balgiu & Adîr, 2017). Indeed, visual imagery seems to work like visual perception (Kosslyn 1973; Shepard & Metzler 1971) both from a cognitive and neural perspective, i.e. retinotopic representations (Pearson & Kosslyn, 2015). Visual imagery may integrate multimodal information, including the raw sensory image (Borst et al., 2006; Hatwell & Cazals, 1988), as well as haptic signals which readily inform visual imagery. Imagery therefore seems to use different sensory systems (Pearson & Kosslyn, 2015). Research suggested that visualizing a complex scene and seeing it activate the same cortical regions (Farah, 1984; Klatky & Lederman, 1993). Mental representations of haptically perceived objects show similarities with visual imagery effects. For example, mental scanning was shown to increase with spatial distance in both visual and haptic imagery (Kosslyn, 1973; Röder & Rösler, 1998). This was also observed in mental rotation tasks (Dellantonio & Spagnolo, 1990; Prather & Sathian, 2002; Shepard & Metzler, 1971). Furthermore, although shape seems to be more important than texture for visual categorization, in haptic and bisensory categorization, shape and texture may be roughly equal (Cooke et al., 2007). Familiar objects are better recognized than unfamiliar ones, because 11 brain regions are common to both visual object imagery and haptic perception of the familiar shape (Lacey & Sathian, 2014). Object imagery and haptic perception of an unfamiliar shape seem to share only four regions, of which only one showed a cross-task correlation (Lacey & Sathian, 2014), except in the case of spatial imagery (Mechelli et al., 2004). Thus, the constituent parts of an unknown object should be explored in their entirety and assembled into a global shape representation via spatial imaging processes (Lacey & Sathian, 2014). In the network parts of spatial imagery and unknown haptic shape perception, the Lateral Occipital Cortex (LOC) appeared driven by parietal lobe, with complex interference between posterior parietal and somatosensory lobe for finer sensory activity. These findings seem consistent with the notion of ascending pathways in somatosensory cortex and the role of cortex in and around the intraparietal sulcus (IPS) in spatial imagery (Lacey & Sathian, 2014). For some scholars, proprioception and kinesthesia are used interchangeably (Lacey & Santhian, 2014). Hence the interest in working with palpable and non-palpable objects in a spatial imaging context (Denis, 1989).

The abovementioned literature supports the idea that visual and haptic perception both enrich mental imagery and thereby support cognition and creativity. The field of embodied cognition goes a step further, arguing that bodily interaction may not only feed cognition but also directly contribute thereto. Embodied cognition is rooted in several theoretical frameworks (from e.g., philosophy, neuroscience, psychology) assuming that the body is a constituent of the mind rather than a passive instrument serving the mind (Leitan & Chaffey, 2014). It supports a situated cognition approach, implying that cognition can be partly off-loaded onto the environment through the body (Wilson, 2002; Wilson & Golonka, 2013). For example, physical manipulation may reduce cognitive workload with comparison to mental manipulation and leave cognitive resources available for other tasks. This off-loading can take the form of externalized cognition (when manipulating the problem helps us think about it and solve it), or can be symbolic, when the purpose of the activity is unrelated to the manipulation task (Wilson, 2002). Examples of symbolic off-loading include automatic behaviors such as gesturing while speaking (Iverson & Goldin-Meadow, 1998; Krauss, 1998), which is not deliberate nor formalized, but helps to *"grease the wheels of the thought process"* (Wilson, 2002, p. 629).

In addition to specific or unspecific object manipulation, creativity may develop under certain sociocognitive conditions. Individuals mobilize their specific skills (Baharom et al., 2013; Huang et al., 2020) in contexts allowing them to develop intrinsic motivation (Amabile, 1988; Carré & Fenouillet, 2019; Guay et al., 2000). For Amabile, individuals "are intrinsically motivated when they seek pleasure, interest, to satisfy their curiosity, to express themselves or to surpass themselves in their work" (1993, p. 188). Moreover, in a group context, individuals may be affected, touched, by the collective creation (Amabile et al., 2005). The development of creativity may greatly vary with group dynamics, motivation (Guay et al., 2000; Carré & Fenouillet, 2019) and the way in which individuals identify with each other and with the group (Postmes et al., 2013). In groups, cooperation can lead to the creation of functioning norms and artefacts relying on the negative and positive strategies developed by the interacting individuals (Bales, 1950; Brauner et al., 2018). These strategies themselves may be taken in a game of non-verbal communication guiding decision-making (Ekman & Friesen, 1969; McNeil, 1992). Similarly, manipulation may be successful when it identifies an object in a spatial and proprioceptive field of use - that is, situated body movements. Also, when there is low arousal, attention can be diverted from staying in a global spatial area to a local spatial area. In short, these are all bottom-up-descending mechanisms assumed to facilitate the work of elaboration and creation (Sack et al., 2008).

With regard to 'mental imagery', many cognitive processes also used in perception appear to be activated through top-down pathways. Both imagery and perception activate a visual buffer (Santarpia et al., 2008): On the one hand, the cognitive process by which sensory information is represented in working memory (MacInnis & Price, 1987) and on the other hand, mental imagery which can be self-generated or result from perception.

The potential impact of object manipulation on cognitive processes pertaining to creativity opens up the possibility to set out an inspirational strategy in the innovation process. The underlying principle would be to allow individuals or groups to perform motor manipulation of inspirational objects to stimulate creativity. This raises the following research questions: Is motor manipulation (visual + haptic senses, multisensorial imagery and embodied cognition) more efficient than mental manipulation (visual sense and imagery only) to support creativity? And if so, is it related to the inspirational properties of the objects (externalized cognition), or merely to a psychophysiological arousal of the haptic system (symbolic off-loading)? In other terms, is the impact on creativity object-dependent, or object-independent?

We investigated these research questions in an industrial application field. The engineering sector recently introduced a disruptive manufacturing process, namely Additive Manufacturing, likely to give rise to disruptive product innovation. However, to overcome design fixations related to traditional manufacturing processes, it appears necessary to provide designers with inspirational material emphasizing the potential of Additive Manufacturing. Some of these inspirational tools are based on cards (Schumacher et al., 2019; Yang et al., 2019) detailing and illustrating process specificities, hence stimulating only the visual channel. Others use a set of tangible objects (Blosch-Paidosh & Shea, 2019; Valjak & Bojcetic, 2019; Watschke et al., 2017). The latter are based on the assumption that motor manipulation (adding the haptic channel to the visual one) may enhance the generation of creative ideas and concepts (Rias et al., 2017). Consistently, Lang et al. (2021) conducted an experiment to compare the use of tangible objects vs cards displaying the same Additive Manufacturing opportunities. Their results showed the superiority of tangible objects to inspire creative solutions and take better advantage of the manufacturing process (Lang et al., 2021). However, the interpretation of these results is not straightforward, as they did not isolate the impact of motor manipulation: to do so, it would have been necessary to distinguish between seeing a tangible object demonstrating the concept and using both visual and haptic modalities to grasp this concept. This was the aim of the present study, and we first expected (Hypothesis 1) that visual-haptic manipulation of objects would increase creativity with regard to visual-imaginative manipulation (a situation in which one can see but not touch or handle the objects, and can manipulate them only mentally).

Furthermore, to distinguish between object-dependent (externalized cognition) and object-independent (symbolic off-loading) stimulation, we compared a set of inspirational vs basic objects. We used the same context of Additive Manufacturing in engineering design, and used a sample of objects illustrating the opportunities of the process (Lang et al., 2021; Segonds et al., 2021) vs a set of basic geometrical volumes. Following previous research conducted on inspirational material for promoting Additive Manufacturing (Blosch-Paidosh & Shea, 2019; Schumacher et al., 2019; Valjak & Bojcetic, 2019; Watschke et al., 2017; Yang et al., 2019), we hypothesized that inspirational objects will lead to more creative solutions than basic objects (Hypothesis 2). Finally, consistent to an embodied cognition approach, we hypothesized that the effect of inspirational objects on creativity would be highest in the visual-haptic manipulation condition (Hypothesis 3). The above-mentioned framework assumes that problem solving or imagining would be more effective when using our bodies to offload information and simplify the nature of the cognitive processing (Wilson & Golonka, 2013). Thereby, a smart task-specific device like the inspirational objects for Additive Manufacturing may help solve the creative task. Specific gesturing actively and directly involving the body in the execution of the task may simplify its computational workload and activate mirror neurons (Foglia & Wilson, 2013). Although never tested before, we assumed that such task-specific gesturing would be more impactful on performance than symbolic off-loading on unspecific objects. In the following section, we detail the study protocol which enabled us to test these three hypotheses.

Method

Participants

$N = 136$ volunteers, distributed in 34 groups of 4 members, participated in the study. They were all 4th-year engineering students at CESI School of Engineering in France. The participants were classmates recruited during their Innovation course. They all signed a consent form and their participation was independent from the outcome of the course.

Materials

The experiment took place in a room at the Research and Innovation department of CESI Engineering School in Paris. Each group participated in a separate session. The participants interacted while sitting around a table. The experimenter stayed in the same room but sitting at a separate table, where all the material was stocked: consent forms, sets of objects, set of colored markers and sheets of paper. The recording setup, shown in Fig. 1, included three cameras and an audio recorder. Two cameras were placed at one side of the interaction table, one providing a top view and the other a frontal view. The third camera was placed at the opposite side of the table and focused on the actions performed on the objects. The audio recorder was placed on the interaction table.

A set of 11 *Inspirational Cubes* which have been previously validated (Lang et al., 2021; Segonds et al., 2021) was selected for the experiment (see Fig. 2). They illustrate some opportunities of Additive Manufacturing, which is a generative manufacturing process enabling a physical object to be made layer by layer from a digital model (Attaran, 2017). Thereby, the process overcomes several limitations of traditional manufacturing (e.g., machining, casting, forging) and solves a number of complexities (e.g., shape complexity, hierarchical complexity, functional complexity, material complexity; Gibson et al., 2021). These opportunities of Additive Manufacturing make it possible to improve existing products, or even to manufacture objects that could never have been manufactured before (Thompson et al., 2016). The *Inspirational Cubes* we used demonstrate the following 11 opportunities: Embedded components, Infilling, Auxetics structure, Material choice, Multimaterials, Nonassembled mechanisms, Topology optimization, Monobloc, Texture, Microstructure variation, and 3D-scanned objects (see Lang et al., 2021, for a full explanation of each opportunity and each inspirational cube).

A set of 11 *Basic Volumes* was adapted from the Creative Mental Synthesis Task material (CMST; Finke et al., 1992). We made 3D-printed versions of 11 stimuli (see Fig. 3) representing basic geometrical elements to be combined into three-dimensional configurations (Finke et al., 1989). Furthermore, these volumes are the basis of industrial creation and manufacturing. Finally, they may not induce imagery (memory, sensorimotor pathways…) but may induce creative combinations exhibiting their own properties.

Experimental conditions

Two independent variables were operationalized, following a between-subject design: the *Manipulation* variable including two conditions (*visual-haptic* vs *visual-imaginative*) and the *Objects* variable (*Inspirational Cubes* vs *Basic Volumes)*. Their combination resulted in a 2 × 2 factorial design, as shown in Table 1.

Procedure

The experiment lasted about 45 min and started with the participants signing a consent form. It included two main phases: pre-inventive and inventive. At the end of the session, the experimenter debriefed the goals of the experiment to the participants and answered their questions.

Pre-inventive phase

The pre-inventive phase was designed to elicit the divergent process of creativity (Palmiero & Piccardi, 2020) and lasted 17 min. During the first 2 min, the experimenter presented the Objects (i.e., *Inspirational Cubes* or *Basic Volumes*) by placing them at the center of the table, and each participant was asked to choose three of them. Group members were allowed to choose the same objects and share them. According to the *Manipulation* condition, the objects could be touched and handled (i.e., *visual-haptic*) or not (i.e., *visual-imaginative*). At the end of the first 2

Fig. 1. The experimental setup.

Fig. 2. Inspirational Cubes used for the experiment.

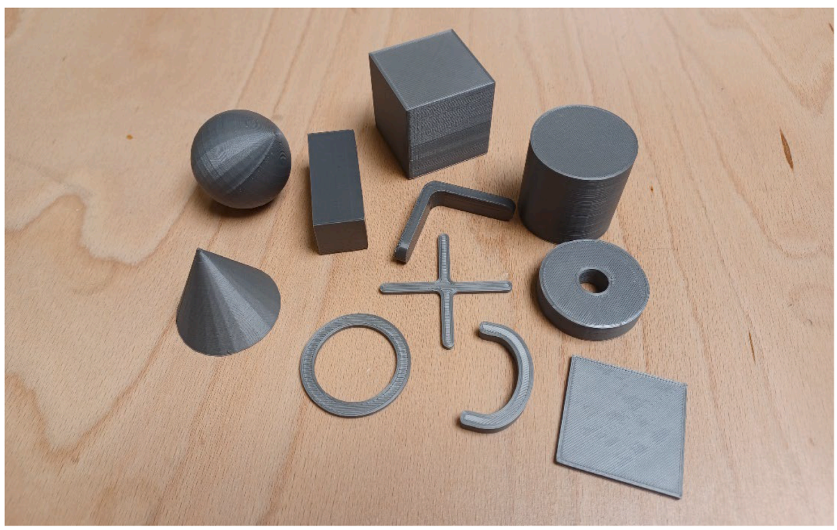

Fig. 3. Basic Volumes adapted from the CMST material (Finke et al., 1992).

Table 1
Distribution of participants across the experimental conditions.

Manipulation\Objects	*Inspirational Cubes*	*Basic Volumes*
Visual-haptic	$N = 36$ participants	$N = 32$ participants
Visual-imaginative	$N = 36$ participants	$N = 32$ participants

min, the experimenter removed the unchosen objects from the table and gave the instructions about the task.

The participants were asked to imagine abstract structures by mentally manipulating their three chosen objects. These could be rotated, made smaller, enlarged or put together, but their overall structure had to remain constant. The participants were asked to follow a "think aloud" protocol: they had to verbalize, in turn, their mental manipulations (Ericsson & Simon, 1980), without making judgements about each other's ideas but could ask questions or revive an idea.

During the pre-inventive phase, the experimenter moderated the interaction when necessary.

Inventive phase

The inventive phase was designed to elicit the convergent process of creativity (Palmiero & Piccardi, 2020). After the 15-minute discussion during the pre-inventive phase, the experimenter introduced new instructions. Each participant was asked to create three products derived from the objects chosen during the previous phase: a tool, a sport item and a jewel. To create these products, the same types of mental manipulation of the objects allowed during the pre-inventive phase were encouraged. Again, the objects could be touched or not according to experimental condition. Colored markers and sheets were available at the center of the table. The participants were asked to use them to create one card for each product, containing a drawing scheme, a title and a brief description. Examples of ideas produced by the participants are shown in Fig. 4. As for the pre-inventive phase, the experimenter only intervened to moderate the interaction if needed.

Results

Assessment of creative performance

The 415 ideas generated during the experiment were evaluated by two expert judges each along 6 creativity criteria selected from the literature (Amabile, 1996; Balgiu & Adir, 2017; Cseh et al., 2016; Lubart & Sternberg, 1995; Palmiero & Picardi, 2020; Palmiero et al., 2015; Tam et al., 2016). Inter-judge agreement proved satisfactory: Novelty ($\alpha = 0.714$), Combination ($\alpha = 0.716$), Aesthetics ($\alpha = 0.720$), Illusion ($\alpha = 0.785$), Function ($\alpha = 0.764$) and Response to need ($\alpha = 0.624$). Furthermore, the 6 criteria show a strong inter-index reliability ($\alpha =$

Fig. 4. Examples of ideas produced by the participants.

0.984) and were then aggregated into a single *Creativity score*.

Annotation of behavioral data

While creative performance was an individual variable, behavioral data were analyzed at the group level. Thirteen behavioral variables were manually annotated[1] from the video recordings with Anvil software:

Concentration: This criterion refers to all manifestations of attentional focus or distraction during manipulation. It relates to body movements (withdrawal, moving towards the group), but also to words and expressions that indicate a relaxation of attention (talking about something else, cutting off the dynamic to change the subject, etc.) or a resumption or acceleration of concentration.

Regulation: Refers to strategic behaviors that facilitate re-focusing towards manipulation. It is also the way of dealing with the situation to find a solution: standing up, looking at oneself, cognitive logics (stacking, assembling, nesting, aesthetics, shape, color, material, weight, ideas; Lubart & Sternberg, 1995).

Affects: Refers to all manifestations of positive or negative emotions during manipulation (e.g., pleasure, disgust, irritation; Amabile, 1996).

Manipulation: Refers to several units of gestures that describe a phase of action. From the preparatory phase where the limbs move slightly, anticipating the action, to the stroke where the peak of effort is delivered, theses phases reflect the cognitive, emotional and/or physical efforts to work the objects (McNeil, 1992).

Body: Refers to the way in which the individual holds and moves when handling an object (Ekman & Friesen, 1969; McNeil, 1992).

Address: Refers to the ways in which the individual speaks when performing object manipulation (McNeil, 1992). Either towards the group, towards oneself, or towards an interlocutor (experimenter or a member of the group).

Deictics: Refer to the movements of pointing at an object or speaker, or at oneself. These movements help to frame the temporal and spatial context of the manipulation (McNeil, 1992).

Self-adaptors[2]: Refer to movements that satisfy personal needs: self-contacting gestures (arms, hands, legs, chest, face).

Other-adaptors: Touching someone (generally hands, legs, arms.…).

Object-adaptors: Touching objects (manipulations).

Positive strategies: Refer to verbal expressions or words that facilitate, encourage interpersonal or group relationships, facilitate the work being handled (Bales, 1950; Brauner et al., 2018).

Negative strategies: Refer to expressions, words that go against the interpersonal or group relationship, against the work of manipulation (Bales, 1950; Brauner et al., 2018).

Elaboration: Refers to words or expressions during physical or mental manipulations: motor (use, functionality), spatial (indicators, transformations) visual (basic, pictorial), emotional (emotions, moods), reasoning (facts, counterfactuals), or level (Ericsson & Simon, 1980; McNeil, 1992; Plamiero & Piccardi, 2020).

All behavioral variables were submitted to a Principal Component Analysis which highlighted four components. The first one ($\alpha = 0.818$) gathered Concentration, Affects, Positive strategies and Body: we renamed this component *Facilitation* as these behaviors can be interpreted as providing attentional, affective, communication and postural support to the activity. The second component ($\alpha = 0.807$) gathered variables directly contributing to the task at hand: Regulation, Manipulation, Deictics, Self- and Object-adaptors, Address. We renamed it *Operations*. The third component contrasted Other-adaptors on the one hand and Negative strategies on the other hand. As these behaviors seem to be delivered in response to the activity, we renamed the component *Reactions*. However, because the two variables were antagonistic, they could not be aggregated and we kept both of them for the analysis. The fourth component relied on a single variable, *Elaboration*. We therefore kept five behavioral variables for the inferential analyses: Facilitation, Operations, Alter-adaptors, Negative strategies and Elaboration.

Test of hypotheses

Creativity score and behavioral variables were submitted to an Analysis of Variance along a 2 (Objects: Inspirational Cubes vs Basic Volumes) x 2 (Manipulation: Visual-Haptic vs Visual-Imaginative) factorial design.

Hypothesis 1 assumed that Visual-Haptic manipulation would increase creativity with regard to Visual-Imaginative manipulation. This effect was supported, as Manipulation significantly impacted the individual level of Creativity ($F(1127) = 5.49$, $p = 0.021$, $\eta^2p = 0.041$), which was higher in the Visual-Haptic condition ($M = 2.66$, $SD = 0.95$) with comparison to the Visual-Imaginative condition ($M = 2.37$, $SD = 0.88$). We observed no effect of Manipulation on any behavioral variable measured.

Regarding Hypothesis 2, we observed a main effect of Objects on the individual level of Creativity ($F(1127) = 116.7, p < 0.001, \eta^2p = 0.479$),

[1] One point when we see behavior or manifestation or action. It is about the present moment and not the ongoing process.

[2] A point when the individual touches himself, the other or the object. Adaptors refer to an emotional manifestation not related to consciousness, so they must be linked to the actual manipulation and verbalization.

which was significantly higher with Inspirational Cubes ($M = 3.10$, $SD = 0.83$) than with Basic Volumes ($M = 1.85$, $SD = 0.43$). Hypothesis 2 was then validated.

Moreover, Hypothesis 2 also partly extended to the behavioral dimension of the creative process. Indeed, the Objects also significantly influenced group Facilitation behaviors ($F(1,30) = 7.277$, $p = 0.011$, $\eta^2p = 0.195$), which were increased with Inspirational Cubes ($M = 30.77$, $SD = 18.92$) with regard to Basic Volumes ($M = 17.03$, $SD = 7.58$). The same effect was found with Operations ($F(1,30) = 14.178$, $p = 0.001$, $\eta^2p = 0.321$), which were also more stimulated by Inspirational Cubes ($M = 32.23$, $SD = 21.4$) than by Basic Volumes ($M = 12.92$, $SD = 5.39$). The other behavioral variables showed no significant difference related to the Objects used for inspiring creativity.

Contrary to expectations related to Hypothesis 3, we observed no interaction effect between Manipulation and Objects variables. In particular, there was no interaction effect on Creativity ($F(1127) = 1.04$, $p = 0.310$). Only one behavioral variable showed a marginal interaction effect, namely Operations ($F(1,30) = 3.58$, $p = 0.068$): the number of Operations with Basic Volumes was not affected by the Manipulation condition (Visual-Imaginative: $M = 13.4$, $SD = 4.82$; Visual-Haptic: $M = 12.44$, $SD = 6.2$), whereas with Inspirational Cubes it was higher in the Visual-Haptic ($M = 41.45$, $SD = 25.8$) than in the Visual-Imaginative condition ($M = 23.02$, $SD = 10.8$). All in all, Hypothesis H3 was not validated.

Discussion

Our results highlighted the importance of multisensoriality for stimulating creativity, as a process including visual-haptic manipulation of objects proved to result in significantly more creative productions than visual-imaginative manipulation. Creative thinking appeared to be stimulated by a multisensory manipulation phase (an active and divergent phase) set up before the creative production (convergent phase; Palmiero & Piccardi, 2020). Given the nature of the task, it is possible that the actions simulated during the interpretation of the pre-invented structures played a functional role in mentally generating uses of created objects. In the embodied cognition theoretical framework, this effect can be interpreted in two complementary ways: visual-haptic manipulation of objects may have enabled participants to partly off-load the cognitive task of combining these objects into creative solutions, and it may also have supported creative thinking through unspecific symbolic off-loading.

As previously shown in the domain Lang et al. (2021), we also validated that objects with various complexities (geometrical, structural, functional, materials) yielded more inspiration than basic geometrical shapes. According to our results, *inspirational cubes* were more fruitful in the creative process than *basic volumes* from CMST, probably because they are more disruptive with materials, areas to touch and manipulate. The absence of interaction effect between Manipulation and Objects variables is an interesting result, as it further supports the idea that two distinct embodiment phenomena may have overlapped in our experiment: an unspecific activation of the visual-haptic system (symbolic off-loading), leading to psychophysiological arousal and supporting creative fluency; and a specific cognitive stimulation conveyed by dedicated inspirational material (externalized cognition). The respective effect sizes of these two phenomena shows that inspirational Objects produced larger effects than Manipulation on creativity. As a concrete implication, one may consider that providing inspirational material may be fruitful to creativity whatever the modalities involved: for example, the inspirational cubes could be used in a tangible setup, but also in a digital, augmented or virtual one, the core impact on creativity being likely to show off even in a remote use of the objects.

The absence of interaction effect may also be due to the fact that shape remains more important than texture for visual categorization, even if in haptic and bisensory categorization, shape and texture are considered roughly equal (Cooke et al., 2007). Indeed, the brain may create categories more easily and block the context or environment. Visual and kinesthetic conditions may then become one.

Furthermore, the strength of our research was to show the importance of the group on the creation of artifacts, affects and ideas. Groups, skills, sensitivity with touch, interactions may be key to develop intra-individual creativity and abilities in groups. Each other's body movements may play a role in the spatial-motor and kinaesthetic elaboration. The group can then reinforce the attraction and inspirational power of objects. Moreover, several positive strategies may allow the group to take the object out of its spatial context to create different shapes.

In addition, lots of movements or operations can satisfy personal needs (self and alter - adaptor) because they are likely to activate ascending pathways in somatosensory cortex and the intraparietal sulcus (IPS) in spatial imagery. Activating the cognitive motor area in the pre-inventive phase may facilitate the creative process, because mental imagery may then exploit multimodal (i.e. visual and haptic) information and better benefit from the specificities of the objects.

Finally, mental imagery may rely on specific visual and kinesthetic processes, high perceptions (bottum-up), and complex cognitions (top-down) which may strongly activate ascending pathways depending on the Objects more than on Manipulation. This could contribute to improving practice for engineers, particularly for using additive manufacturing and/or during their training at school. We could imagine setting up manipulation workshops to create new work standards in engineering training projects.

This study also held several limitations. Firstly, increasing the sample size could be necessary to understand the interplay of such complex phenomena as embodied cognition, mental imagery and creativity more deeply. Furthermore, our experiment was conducted in an academic context, so participants can be influenced by the environment and relationship with their colleagues and trainers. Professional experience of participants was also limited because they were still at school. Their working memory may have been less developed than senior engineers, which can have influenced mental imagery and creativity. All in all, our results supported the inspirational power of dedicated material (here objects demonstrating the opportunities of Additive Manufacturing), the potential of introducing visual-haptic manipulation into the creative process (both for symbolic off-loading and externalized cognition), and the likely independence of these two phenomena to stimulate creativity in engineering teams. In the future, these findings may be further studied and implemented both in training or in professional contexts in order to contribute to innovation in a globalized world.

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CRediT authorship contribution statement

Amandine Cimier: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Beatrice Biancardi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Jérome Guegan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Frédéric Segonds:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Fabrice Mantelet:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Camille Jean:** Writing –

review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Claude Gazo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Stéphanie Buisine:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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