1 INTRODUCTION

Mental imagery is the experience of visually, or with another sense, perceiving an image within one's own mind (Pearson 2007, Nanay 2018, Maciel et al. 2021). Whilst there is an abundance of research into the workings of mental imagery, the cognitive function is still not fully understood, due largely to the personal and subjective nature of mental imagery experiences (Richardson 1991). Whilst research on the phenomenon of mental imagery is largely psychology-based and on psychological conditions (for example post-traumatic stress disorder) (Holmes & Mathews 2010), it is widely acknowledged that it has significant importance across many other scientific and creative fields (Kozhevnikov et al. 2013) and an almost casual use in day-to-day life for many people (Pearson 2007, Casakin & Kreitler 2011).
The design industry spans a large variety of different professions and roles, including that of product design engineering. It is widely assumed that designers rely heavily on mental imagery, in particular on visual mental imagery, and that visual mental imagery is an essential part of design cognition (Hart & Hay 2022). However, research shows that there are considerable variations in the experience of mental imagery, from different sense imagery (Floridou, Peerdeman & Schaefer 2022) to differing levels of clarity between individuals (Gallagher 2019, Zeman 2021). There are even reports of distinguished animation artists (Gallagher 2019) and visual artists (Zeman 2021) reporting that they experience no visual imagery, and while product design engineering is a very different type of design to art and animation, there are similarities in the assumptions made regarding creative professions and visual mental imagery (Hart & Hay 2022). Despite the evidence, there is a distinct lack of research into how designers utilise and experience mental imagery in product design engineering, particularly outside of the visual domain.
This paper provides an overview of the development of a framework for researching mental imagery, as well as current literature found to support its use in a product design engineering context. The framework will support structured research on mental imagery which, given the different and interconnecting elements, can be a relatively unstructured topic. Within product design engineering, the framework will allow for necessary discussion and help to find important areas for further research. This will create a basis for future work that considers all elements and viewpoints of a designer's experience of mental imagery within the design process.

2 DEFINING MENTAL IMAGERY IN DESIGN COGNITION RESEARCH

The field of mental imagery research is expansive and ranges from psychological uses for mental imagery (Holmes & Mathews 2010) to benefits of imagery utilisation in the design industry (Dahl et al. 2001, Goldschmidt 2007). This paper was developed from a literature review covering mental imagery research in design, with the scope of the literature ranging from psychology to design in order to gain an in-depth understanding of the phenomenon. The literature was sourced using a range of trusted databases and journals, and keywords and phrases that related to both psychology and design research. During this initial literature review it was realised that research on the topic of mental imagery is complex and interconnecting, with wide differences between individual experiences. In order to provide more structure to the review, a framework was developed for researching mental imagery and applied within a design cognition context.

2.1 An overview of the neurobiology and psychology of mental imagery

It is widely acknowledged that mental imagery involves a complex brain network (Pearson 2019), with evidence that activated brain regions are dependent on the form of imagery being engaged (Richardson 1991). For example, neuroimaging revealed that visual mental imagery activates regions in the occipitotemporal cortex and the ventral visual stream, while the parietal cortex is active during spatial imagery (Dijkstra et al. 2019). Mental imagery is often described as a "perceptual experience" (Maciel et al. 2021) in which the mind behaves as if it is experiencing a physical sense. Evidence does suggest that the mental imagery activity can result in some small physical reactions within the body, such as the pupils dilating or constricting in response to imagining light or dark scenarios and objects, in the same way as looking at a bright light (Laeng & Sulutredt 2014, Zeman 2021), or instinctively sniffing during olfactory imagery (Bensafi et al. 2012).

This is a peer-reviewed, accepted author manuscript of the following paper: Macfie, R., Hay, L., & Rodgers, P. (Accepted/In press). Conceptual viewpoints on mental imagery in product design engineering: a framework for researching mental imagery in design cognition. Paper presented at 24th International Conference on Engineering Design, Bordeaux, France.

It has been determined that other cognitive functions are needed for mental imagery processing due to the complexity of the task, as is discussed further in this paper. The cognitive functions used with mental imagery may differ slightly depending on the task being undertaken, from daydreaming to visual imagination imagery, or even dreaming (Palmiero et al. 2016). For example, Zeman (2021) found that an individual asked to visualise a flower would need to use functions associated with being awake and attentive, whilst daydreaming often does not require someone to be fully attentive.
Over the decades, psychology and neuroscience have attempted to explain what occurs during mental imagery at a cognitive and neural level, and what factors may influence it. However, although mental imagery seems to play an important role in the day-to-day lives of many people (Kozhevnikov et al. 2013), there is still considerable scientific disagreement on what is involved and a number of competing hypotheses and models. This disagreement leads to added complexity in researching the function within design cognition and creates a solid basis for the development of a supportive framework.

2.2 Developing a framework for mental imagery research

Researching a topic as complex and subjective as mental imagery is a difficult task. Each person can have an entirely different experience given that it exists entirely within one's own mind (Maciel et al. 2021), but it is suggested with this framework that there are three fundamental conceptual viewpoints of mental imagery. Considering literature from both psychology and design it was determined that these viewpoints consist of imagery modalities, the dimensions of imagery ability, and imagery processes. Imagery modalities consists of the different senses in imagery, as well as the connection and impact of emotion; dimensions of imagery ability are topics such as imagery vividness, spatial ability, and measurements of imagery; and imagery processes involves tasks such as image generation and retention, or the use of memory images. Whilst these can be standalone topics, it is necessary to keep in mind how closely they all interact with each other. For example, dimensions closely interacts with modalities in that individuals can have differing levels of vividness across different modalities (Maciel et al. 2021), and memory imagery (process) can impact on emotion and modalities (Taruffi & Küssner 2019). Figure 1 provides a graphic interpretation of the framework, and depicts the three viewpoints surrounding the main topic, with all viewpoints interconnecting, and then converging back into the centre. This framework has been developed with the expectation that it can be employed to research mental imagery within different fields. Exactly that has been done here for product design engineering, and the remainder of this paper is a discussion of the literature findings as verification of the framework.

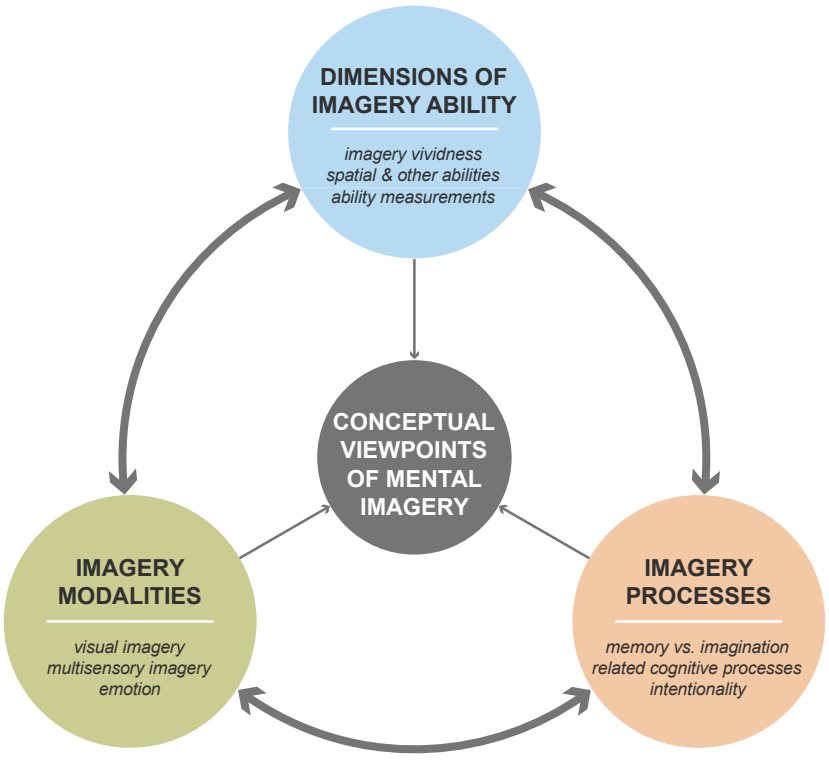

Figure 1: Framework for researching the conceptual viewpoints on mental imagery

3 MENTAL IMAGERY IN PRODUCT DESIGN ENGINEERING

As mentioned, it is regularly assumed that design and mental imagery are consistently closely intertwined (Goldschmidt 1991, Hart & Hay 2022). This assumption, however, overlooks that the mental imagery experience can vary greatly between designers, design processes, and design tasks. It has been shown throughout research that designers are capable of creating entirely within the "mind's eye" (Athavankar 1997) or despite having no experience of mental imagery at all (Gallagher 2019, Zeman 2021). Through the framework developed and detailed above, it is possible to analyse the relevant design research, as well as any psychological research that may contain important insights for design.

3.1 Mental imagery modalities

Commonly, mental imagery is believed to be an entirely visual experience, but in reality, it is a multisensory experience activated through the senses and can include auditory, olfactory, tactile and motor function imagery (Goldschmidt 1994, Maciel et al. 2021). The majority of mental imagery research, particularly within design, focuses on visual imagery, largely disregarding other modalities. One potential reason for this is that it is commonly believed (potentially erroneously) that visual imagery is the most dominant modality that designers use (Bensafi et al. 2012). Whilst visual imagery in particular is useful for problem-solving as it encourages creative thinking and allows for easier simulation both internally and externally (Athvankar 1997, Bilda et al. 2006, Bilda & Gero 2008), it would be naive to assume that other modalities do not have use in design.

3.1.1 Visual imagery

Visual mental imagery, often referred to as “visual thinking”, “visual perception” or “visualisation” (Goldschmidt 1994, Dahl et al. 2001, Kavakli & Gero 2001, Zeman 2021) refers to the act of “seeing” within the so-called “mind’s eye”. It refers to a task that is similar to visual perception (Cui et al. 2007), and is often triggered by information obtained from a stimulus other than a visual representation itself (Kosslyn, Behrmann & Jeannerod 1995), for example music can trigger visual memories (Taruffi & Küssner 2019). Often, visual mental imagery consists of a remembered image, either in its initial form or as a modification of remembered information (Taruffi & Küssner 2019).

In neurobiological terms, there is evidence to suggest that mental imagery and visual perception rely on similar neural mechanisms within the brain (Dijkstra et al. 2017, Dijkstra et al. 2019) and that impacts on visual perception can also impact on mental imagery (Pearson et al. 2011). An example may be found in the binocular rivalry paradigm (Dijkstra et al. 2019). Binocular rivalry describes the visual fight for perceptual dominance that occurs when a person is shown two differing images at one time. In terms of mental imagery, there is evidence that if an observer mentally visualises one of the images first, it produces a bias whereby this is the image they will likely perceive (described by Dijkstra et al. (2019) as having “a priming effect”).

Mental imagery and visual perception can be viewed in terms of so-called “top-down” and “bottom-up” neural connectivity (Dijkstra et al. 2017, Dijkstra et al. 2019). Visual perception occurs from bottom-up influences throughout the visual system, starting from the retina. Dijkstra’s (2017) evidence shows an increase in bottom-up coupling between neurological brain areas during visual perception and top-down coupling during both mental imagery and visual perception, with a stronger response during mental imagery. This suggests a similarity in terms of neurological areas impacted by visual imagery and visual perception (Pearson et al. 2011, Dijkstra et al. 2019, Pearson 2019).

3.1.2 Multisensory imagery

As noted earlier, mental imagery can occur in each of the senses and measuring such will be discussed further in this report. Whilst an individual can experience all forms of imagery, it is also possible for them to experience differing variations, for example one may experience high levels of imagery in every modality except visual (Maciel et al. 2021). Multisensory imagery has a vast range of applications, including psychological treatments, such as auditory imagery in cognitive behavioural therapy (CBT) (Nanay 2018). There is also evidence that physical sensory practice has immense effects on imaging ability: musicians tend to outperform non-musicians in auditory vividness questionnaires, and perfumers have stronger reported olfactory imagery than the general public (Bensafi et al. 2012). Whilst research into the impact of multisensory imagery in design is extremely limited, it is interesting to consider

whether there is a significance to some of these findings within a design setting, such as theorising if designers have stronger visual imagery because they are trained in a largely visual setting.

3.1.3 Emotion and mental imagery

Research provides strong links between emotion and mental imagery, and suggests that trait empathy differences are linked to higher levels of imagery (Taruffi & Küssner 2019). Mental imagery often has a greater emotional impact than verbal interpretations of potential future situations as it allows for "pre-experiencing" of said situations (Ji et al. 2022) and there is evidence that mental imagery plays a key role in many emotional and psychiatric disorders and treatments (Holmes & Mathews 2010). Additionally, there is some physical evidence that fear imaging produces a stronger response than neutral situational imaging in that, for example, fearful mental imagery has been shown to cause an increased heart rate (Holmes & Mathews 2010). As discussed, multi-sensory mental imagery appears to mimic multi-sensory perception in those that are capable of the experience and evidence suggests that emotional imagery works in much the same way. For example, if an individual has a phobia of snakes, using mental imagery to visualise a snake approaching would cause a similar emotional response as physically watching a snake approach (Holmes & Mathews 2010). Additionally, the nature of an image, as well as the emotional capabilities of the individual, will play a role in the impact an image has; there is evidence that the more vivid visual imagery a person experiences, the more intense and emotional any imagined future events are (D'Argembeau & Van der Linden 2005, Holmes & Mathews 2010).

3.2 Dimensions of imagery ability

The mental imagery experience is different for each individual and is not one-size-fits-all, with individuals experiencing mental imagery at varying ability and clarity (Kavakli & Gero 2001). Mental imagery is a largely personal experience and therefore subjective (Richardson 1991) and while differences can occur across different modalities, the research on dimensional abilities largely refers to visual imagery. Imagery occurs entirely within an individual's mind and can therefore only be directly observed by the person experiencing it (Palmiero et al. 2015, Milton et al. 2021). Whilst mental imagery has been shown to improve both experience and outcome in design, many designers claim to refuse to use it, or cannot use it due to reduced vividness (Dahl et al. 1999, Dahl et al. 2001). With respect to dimensional ability, Gallagher (2019) provided evidence that creative individuals and designers can successfully design despite having low or no visual imagery, and so it can be deduced that the assumption that mental imagery is key to design (Bilda & Gero 2008) is not necessarily correct.

3.2.1 Mental imagery vividness

The spectrum of mental imagery clarity is normally referred to as the "vividness" of mental imagery. Individuals report anywhere from a complete lack of mental imagery to extremely vivid mental imagery (Cui et al. 2007, Kozhevnikov et al. 2013, Pearson 2019, Bainbridge et al. 2021, Zeman 2021), though the research primarily covers clarity or vividness differences in the visual modality. Whilst differences in visual imagery vividness have been discussed for decades, it was only in 2015 that the extremes of aphantasia and hyperphantasia were named by Professor Adam Zeman (Bainbridge et al. 2021, Zeman, Dewar & Della Sala 2015). Aphantasia is the complete lack of visual mental imagery (Gallagher 2019, Zeman, Dewar & Della Sala 2015), while hyperphantasia describes imagery so vivid it can be similar to a physical sensation (Bainbridge et al. 2021). Aphantasia affects roughly 1-3% of people, although most adults knowingly living with aphantasia do not realise it exists until they are into adulthood (Rhodes 1981), whilst hyperphantasia affects around 3-7% (Zeman 2021). Milton et al.'s (2021) studies suggest people with hyperphantasia perform better in memory tests, whilst people with aphantasia tend to be less extraverted and open than those with hyperphantasia. Despite the lack of visual mental imagery, aphantasia does not usually have a negative impact on life experience (Bainbridge et al. 2021) nor does it necessarily impact on creative abilities (Gallagher 2019, Zeman 2021).

3.2.2 Spatial and other abilities

According to Allan (2010), the components of imagery spatial ability include mentally seeing in 2-dimensions (2D) within a 3-dimensional (3D) environment, mentally rotating objects, and mentally seeing objects in scale within mental imagery. There is evidence that while those with diagnosed or self-diagnosed aphantasia consistently score as such on visual imagery tests, they tend to still score highly

on mental rotation and spatial ability tests (Keogh & Pearson 2017). This implies potentially separate functions for different abilities, but there is a lack of further research into this occurrence.
Mental scanning is a task where an individual perceives, within imagery, moving from one point to another, usually engaging visual imagery (Gallace 2013). Another example of a difference in dimensional ability is the timing for mental rotation (Pearson et al. 2011) and the speed at which individuals manipulate or process images within their mind: there is evidence that the more mental rotation that a task requires, the longer said task will take (Kosslyn, Behrmann & Jeannerod 1995). Researchers in mental rotation differences tend to rely heavily on theories of embodied cognition and some suggest that this plays a role in differences (Voyer et al. 2020). Whilst standard definitions perceive cognition as a computational activity with the brain performing the operation alone, embodied cognition provides a more complex and inclusive view (Tedjosaputro & Shih 2018). Embodied cognition views thinking as an active relationship between the body, the mind and the surrounding environment, where cognition is the body's interaction with the world (Tedjosaputro & Shih 2018).

3.2.3 Measurement systems

Measurement systems have been developed across the field of mental imagery psychology research as a way of quantifying the different imagery experiences. The most common method of measurement within psychology are written or verbal self-report questionnaires. One example of these questionnaires are spatial or mental rotation ability tests which use pictorial questions to ask the responder to match up rotated images (Peters et al. 1995). Whilst the exact nature, appearance and content of visual mental imagery is difficult to measure, the Vividness of Visual Imagery Questionnaire (VVIQ), first developed by psychologist David Marks in 1973 (Bainbridge et al. 2021), is a written questionnaire designed to provide a way to measure vividness of mental imagery through scenario-style questions (Kozhevnikov et al. 2013, Zeman 2021). Further questionnaires have been created in an attempt to look at multisensory imagery vividness, such as the Plymouth Sensory Imagery Questionnaire (PSI-Q), which was developed to measure appearance, sound, smell, taste, bodily sensation, feeling and touch imagery (Andrade et al. 2014). In psychology, so-called "social desirability measurements" have been suggested to minimise the subjective nature of mental imagery questionnaires. Social desirability scales are a psychological measure that were designed to test whether individuals answer self-response tests in what is seen as a culturally approved way by presenting questions and scenarios seen to describe improbable or negative behaviours (Holtrop et al. 2021). It is believed that if a person responds to many of these claims in a way that depicts them as an overly virtuous person, they are more than likely lying or answering in what they deem to be a socially desirable way (Holtrop et al. 2021).
Whilst still lacking in evidence, other measures of imagery vividness have been suggested which could provide a more objective form of measurement (Bainbridge et al. 2021). According to Cui et al. (2007), it is possible that the vividness individuals experience is directly linked to the activity of their visual cortex, and it has been suggested that there could be a way to develop a method using modern technology, for example fMRI, which tracks and measures the visual cortex. There is further evidence in Pearson, Rademaker and Tong (2011) which shows that subjective vividness ratings can predict level changes in the visual cortex during mental imagery. More recently, there has been evidence that pupil response may be an appropriate measure of aphantasia. Hawley's (2022) work has shown that when asked to mentally visualise a light vs a dark image, people living without aphantasia's pupils respond as they would to visually seeing a light vs a dark object, whereas with aphantasia, there is no pupil response when asked the same.
Measurement systems for mental imagery within design itself are lacking, but one method for understanding experiences during design tasks is protocol analysis. Protocol analysis is a psychological method that comes under the banner of self-reporting and allows for the analysis of mental processes through verbal reports (Hay et al. 2017, Lawrie, Hay & Wodehouse 2022). In design research, protocol analysis is undertaken through visual and audio recordings of a designer either during or after a design task, following which the recordings are coded and analysed according to a coding scheme (Gero & McNeill 1998, Hay et al. 2017, Lawrie, Hay & Wodehouse 2022). The recordings can include verbal responses, sketches, and actions (Hay et al. 2017). Although the high level of data gathered in protocol studies makes it a very time-consuming analysis method, the detailed insight into the internal process of a designer, which is a subjective experience, makes is a popular method in design research (Hay et al. 2017).

3.3 Mental imagery processes

Mental imagery processes, meaning the imagery actions and tasks undertaken by an individual, can take many different forms and styles, from the generation, transformation and inspection of imagery (Rademaker & Pearson 2012) to perceptual or active imagery (Kavakli & Gero 2001). Kosslyn, Behrmann and Jeannerod (1995) suggest that mental imagery involves a number of working processes that include forming, scanning, interpreting, maintaining and transforming images. In the same literature, mental imagery processes are grouped into four categories: learning and memory, perception and action, information processing, and reasoning using imagery (Kosslyn, Behrmann & Jeannerod 1995). The term "interactive imagery" has been used to describe the task of refining and transforming images within the mind due to the ease at which individuals can interact with and manipulate the shapes (Goldschmidt 1991). The experience of mental imagery itself allows individuals to access thoughts, senses, and emotions entirely within their mind and provides a strong base for creating new ideas (Palmiero et al. 2016).

One often discussed difference in mental imagery processes are the clear distinctions between memory imagery and imagination imagery (Rhodes 1981, Dahl et al. 1999, Dahl et al. 2001, Pearson 2007, Pearson 2019). Whilst mental imagery can include the creation of new, "imagined" ideas and images, it can also be as simple as remembering an image or idea that has already been defined within memory (Dahl et al. 1999, Dahl et al. 2001, Kavakli & Gero 2001). Different imagery processes can impact on problem-solving in design: memory imagery allows the designer to draw from their own experiences and knowledge to design a product, whilst imagination imagery can allow them to create more novel ideas (Dahl et al. 1999, Dahl et al. 2001). Evidence suggests most designers will automatically begin by focusing on memory imagery before moving to imagination imagery, if they are capable, likely due to it being simpler to start from something they know and have experienced (Dahl et al. 2001). For this reason, it is somewhat unsurprising that Gero and Milovanovic (2020) found that designers who are experienced in their fields tend to think and work faster and more intuitively than novice designers. Whilst both memory and imagination imagery are described as useful for the design process, imagination imagery has been suggested as more efficient for product ideation as it appears to allow for a more novel product (Dahl et al. 1999, Herd & Mehta 2019).

One way in which we can discuss imagery use is through intentionality and whether mental imagery is experienced voluntarily, meaning an individual can willingly call up images within their mind, or involuntarily, such as whilst experiencing intrusive thoughts (Floridou, Peerdeman & Schaefer 2021). There is a simplicity that comes with using mental imagery in design (Goldschmidt 2007) due to the potential reduction in tools needed and the ease with which new ideas can be generated. Furthermore, as design is heavily dependent on context (Goldschmidt 2007), evidence suggests that a designer's experience of visual imagery during the design process can have a big impact on both the novelty and usefulness of the final design (Dahl et al. 2001). It can also increase the level of empathy featured in the design process and lead to a larger focus on the customer's perspective (Dahl et al. 2001). Additionally, the transformation from mental imagery to physical visualisation creates a form of balance between fantasy and reality that allows for more creative and novel designs (Allen 2010). However, evidence suggests that experienced designers are still reluctant to take full advantage of the experience of mental imagery to assist them in design, or so they claim (Dahl et al. 2001). It is possible that this could be explained by intentionality: if a designer assumes that their mental imagery is an involuntary or expected part of the design process, we can theorise that they may be overlooking the potential power of voluntarily creating new ideas within their so-called mind's eye.

There are different steps within mental imagery according to Casakin and Kreitler (2011), and designers alternate between "framing", "making moves" and "evaluating moves" during the design process to navigate their way through problem-solving. An important point raised by Bilda and Gero (2008), is that whilst design obviously occurs during the design process itself, it can also occur out with the physical design environment, and a designer could find themselves struck with inspiration at another time, for example while travelling from work. Through the phenomenon, a designer can have an idea or a design breakthrough at any time, with inspiration coming from even the smallest places (Bilda & Gero 2008).

Mental imagery does come with its own set of issues, such as problems stemming from short term memory – if a designer was to create entirely within their own mind, they would be at risk of forgetting and excluding parts of the final design (Athavankar 1997). One method around this issue is to use mental imagery in conjunction with tools and design methods, such as mind mapping, which in itself is a method

that relies heavily on imagery and the fast processing of ideas within the mind (Athavankar 1997, Bilda & Gero 2008). Techniques such as this encourage the designer to look for creative solutions within their own skill base and knowledge (Allen 2010). As mentioned throughout this paper, the use of mental imagery is an entirely internal process, meaning that many designers live within their own catalogue of images and design can rely on the interaction between this internal process and external processes, such as sketching (Athavankar 1997, Bilda & Gero 2008, Tedjosaputro et al. 2014). Most designers would argue that sketching is an essential step in the design process (Athavankar 1997, Kokotovich & Purcell 2000) and it is a simple yet reliable method of communication and reasoning which encourages the development of ideas (Goldschmidt 1991, Bilda & Gero 2008, Tedjosaputro et al. 2014). Sketching is particularly useful within design teams as it increases communication by allowing ideas and images to be shared more easily (Goldschmidt 2007).

4 CONCLUSIONS

The literature review conducted for this paper provided insight into how mental imagery can be successfully researched within the context of product design engineering. It allowed the development of a framework breaking down the elements involved in mental imagery research. It was found that mental imagery can be split into three conceptual viewpoints that can be viewed interconnectedly with each other: imagery modalities, dimensions of imagery ability, and imagery processes. Whilst this research is limited by the amount of literature on the topic in product design engineering specifically, it was found that psychology research and design research in other domains, such as architecture, could have relevance to the field of product design engineering.

Mental imagery itself is a personal experience with designers able to manipulate the ideas within their minds (Athavankar 1997, Oxman 2002). The subjective nature of the experience leads to different definitions and understandings. This is a particular issue in a field such as design, where individuals are strongly believed to need mental imagery to thrive (Hart & Hay 2022). In this paper, the framework given in Figure 1 was used to structure the literature on mental imagery from across the design and psychology fields. This has allowed a greater insight into the aspects of the mental imagery experience that should be considered when researching the topic in the product design engineering context, as well as providing evidence of the different experiences of mental imagery (Gallagher 2019, Zeman 2021). The use of the framework in respect to product design engineering has allowed for a definition of mental imagery within the field to emerge.

An important detail of the framework that should be considered during mental imagery research is that each of the viewpoints interact with each other. It is difficult to consider one element of mental imagery without keeping the others in mind, particularly when considering how it is experienced within product design engineering. An example of this is that Maciel et al. (2021) found that it is possible that individuals can experience differing levels of mental imagery vividness for different modalities. Given the varying experiences of visual mental imagery in design (Gallagher 2019), it is feasible that different designers utilise different sensory perception at different levels. Additionally, Dahl, Chattopadhyay and Gorn (1999, 2001) found that intentionally of utilising mental imagery within the design process by way of visualising the end user of a product provides a designer with a greater sense of empathy, leading to more useful final products. Given that there is an intricate connection between emotion or empathy and imagery (Taruffi & Küssner 2019), it is feasible that there is a link between intentionality of mental imagery (process) and emotion or empathic ability in design (modality).

This review has uncovered some important literature on the experience of mental imagery in product design engineering. However, there is a significant lack of research on the topic within the relevant field, leading to many questions about how mental imagery is experienced and if it can be better utilised to create stronger solutions. Given that there is still a strong assumption that design and mental imagery are inherently connected but that there is evidence suggesting this is not the case (Gallagher 2019, Zeman 2021), it is worth considering that important aspects are being overlooked. For example, can a designer choose which imagery modality to use during design, or are they able to train their intentionality? For this reason, it is evident that this framework can be utilised further in potential studies as a way of considering the aspects that may be impacting a designer's experience, use or understanding of their own mental imagery during the design process.

REFERENCES

Allen, A.D. (2010) Complex Spatial Skills: The Link Between Visualization and Creativity, Creativity Research Journal, 22(3), pp.241-249.

Andrade, J., et al. (2014) Assessing vividness of mental imagery: The Plymouth Sensory Imagery Questionnaire, The British journal of psychology, 105(4), pp.-547-563.

Athavankar, U.A. (1997) MENTAL IMAGERY AS A DESIGN TOOL, Cybernetics and systems, 28(1), pp.25-42.

Bainbridge, W.A. et al. (2021) Quantifying aphantasia through drawing: Those without visual imagery show deficits in object but not spatial memory, Cortex, 135, pp.159-172.

Bensafi, M. et al. (2012) Olfactory and Gustatory Mental Imagery: Modulation by Sensory Experience and Comparison to Auditory Mental Imagery, in Multisensory Imagery. New York, NY: Springer New York, pp.77-91.

Bilda, Z., Gero, J.S. and Purcell, T. (2006) To sketch or not to sketch? That is the question, Design studies, 27(5), pp.587-613.

Bilda, Z. and Gero, J.S. (2008) Idea Development Can Occur Using Imagery Only, Design Computing and Cognition '08, pp.303-320.

Casakin, H. and Kreitler, S. (2011) The cognitive profile of creativity in design, Thinking skills and creativity, 6(3), pp.159-168.

Cui, X. et al. (2007) Vividness of mental imagery: Individual variability can be measured objectively, Vision research (Oxford), 47(4), pp.474-478.

D'Argembeau, A. and Van der Linden, M. (2006) Individual differences in the phenomenology of mental time travel: The effect of vivid visual imagery and emotion regulation strategies, Consciousness and cognition, 15(2), pp.342-350.

Dahl, D.W., Chattopadhyay, A. and Gorn, G.J. (1999) The use of visual mental imagery in new product design, Journal of marketing research, 36(1), pp.18-28.

Dahl, D.W., Chattopadhyay, A. and Gorn, G.J. (2001) The importance of visualisation in concept design, Design studies, 22(1), pp.5-26.

Davis, J.I. et al. (2012) Four Applications of Embodied Cognition, Topics in cognitive science, 4(4), pp.786-793.

Dijkstra, N. et al. (2017) Distinct top-down and bottom-up brain connectivity during visual perception and imagery, Scientific reports, 7(1), pp.5677-9.

Dijkstra, N. et al. (2019) Between-subject variability in the influence of mental imagery on conscious perception, Scientific reports, 9(1), pp.15658–10.

Dijkstra, N., Bosch, S.E. and van Gerven, M.A.J. (2019) Shared Neural Mechanisms of Visual Perception and Imagery, Trends in cognitive sciences, 23(5), pp.423-434.

Floridou, G.A., Peerdeman, K.J. and Schaefer, R.S. (2022) Individual differences in mental imagery in different modalities and levels of intentionality, Memory & cognition, 50(1), pp. 29-44.

Gallace, A. (2012) Somesthetic Mental Imagery, in Multisensory Imagery. New York, NY: Springer New York, pp.29–50.

Gallagher, J. (2019) Aphantasia: Ex-Pixar chief Ed Catmull says 'my mind's eye is blind', BBC News: https://www.bbc.co.uk/news/health-47830256, accessed 14:15 03/11/2022.

Gero, J.S. and Milovanovic, J. (2020) A framework for studying design thinking through measuring designers' minds, bodies and brains, Design Science, 6.

Goldschmidt, G. (1991) The dialectics of sketching, Creativity research journal, 4(2), pp. 123–143.

Goldschmidt, G. (1994) On visual design thinking: the vis kids of architecture, Design studies, 15(2), pp.158–174.

Goldschmidt, G. (2007) To see eye to eye: the role of visual representations in building shared mental models in design teams, CoDesign, 3(1), pp.43–50.

Hart, E. and Hay, L. (2022) Do you see what I see? Exploring vividness of visual mental imagery in product design ideation, Proceedings of the Design Society, 2, pp. 881-890.

Hawley, J. (2022) Windows to the soul: Pupils reveal 'aphantasia', the absence of visual imagination, UNSW Newsroom: https://newsroom.unsw.edu.au/news/science-tech/windows-soul-pupils-reveal-aphantasia-absence-visual-imagination, accessed 14:17 03/11/2022.

Hay, L. et al. (2017) A systematic review of protocol studies on conceptual design cognition: Design as search and exploration, Design Science, 3.

Herd, K.B. and Mehta, R. (2019) Head versus Heart: The Effect of Objective versus Feelings-Based Mental Imagery on New Product Creativity, The Journal of consumer research, 46(1), pp.36–52.

Holmes, E.A. and Mathews, A. (2010) Mental imagery in emotion and emotional disorders, Clinical psychology review, 30(3), pp.349–362.

Holtrop, D. et al. (2021) Do social desirability scales measure dishonesty?: A think-aloud study, European journal of psychological assessment: official organ of the European Association of Psychological Assessment, 37(4), pp.274–282.

Ji, J.L. et al. (2022) Emotional mental imagery generation during spontaneous future thinking: relationship with optimism and negative mood, Psychological research, 86(2), pp.617–626.
Kavakli, M. and Gero, J.S. (2001) Sketching as mental imagery processing, Design studies, 22(4), pp.347–364.
Keogh, R. and Pearson, J. (2018) The blind mind: No sensory visual imagery in aphantasia, Cortex, 105, pp.53–60.
Kosslyn, S.M., Behrmann, M. and Jeannerod, M. (1995) The cognitive neuroscience of mental imagery, Neuropsychologia, 33(11), pp.1335–1344.
Kozhevnikov, M. et al. (2013) Creativity, visualization abilities, and visual cognitive style, British journal of educational psychology, 83(2), pp.196–209.
Laeng, B. and Sulutvedt, U. (2014) The Eye Pupil Adjusts to Imaginary Light, Psychological science, 25(1), pp.188–197.
Lawrie, E., Hay, L. and Wodehouse, A. [In press] A classification of methods and constructs in design cognition research, Design Computing and Cognition '22.
Maciel, I.M. et al. (2021) Mental Imagery for Multisensory Designers: Insights for Non-visual Design Cognition, in Design for Tomorrow—Volume 1. Singapore: Springer Singapore (Smart Innovation, Systems and Technologies), pp.109–118.
Milton, F. et al. (2021) Behavioral and Neural Signatures of Visual Imagery Vividness Extremes: Aphantasia versus Hyperphantasia, Cerebral Cortex Communications, 2(2).
Nanay, B. (2018) Multimodal mental imagery, Cortex, 105, pp.125–134.
Oxman, R. (2002) The thinking eye: visual re-cognition in design emergence, Design studies, 23(2), pp.135–164.
Palmiero, M. et al. (2016) Editorial: Creativity and mental imagery, Frontiers in psychology, 7
Pearson, D.G. (2007) Mental Imagery and Creative Thought, in Imaginative Minds. British Academy (Proceedings of the British Academy).
Pearson, J. (2019) The human imagination: the cognitive neuroscience of visual mental imagery, Nature reviews - Neuroscience, 20(10), pp.624–634.
Pearson, J., Rademaker, R.L. and Tong, F. (2011) Evaluating the Mind's Eye: The Metacognition of Visual Imagery, Psychological science, 22(12), pp.1535–1542.
Peters, M. et al. (1995) A Redrawn Vandenberg and Kuse Mental Rotations Test - Different Versions and Factors That Affect Performance, Brain and cognition, 28(1), pp.39–58.
Rhodes, J.W. (1981) Relationships Between Vividness of Mental Imagery and Creative Thinking, The Journal of creative behavior, 15(2), pp.90–98.
Richardson, J. (1991) Imagery and the Brain, in Imagery and Cognition. New York: Springer-Verlag, pp.1-45.
Taruffi, L. and Küssner, M.B. (2019) A Review of Music-Evoked Visual Mental Imagery: Conceptual Issues, Relation to Emotion, and Functional Outcome, Psychomusicology, 29(2-3), pp.62–74.
Tedjosaputro, M.A. et al. (2014) Multidisciplinary Design Behaviour Using Sketching and Mental Imagery: A Literature Review and Considerations for Future Research, in ICoRD'15 – Research into Design Across Boundaries Volume 1. New Delhi: Springer India (Smart Innovation, Systems and Technologies), pp.27–37.
Tedjosaputro, M.A. and Shih, Y.-T. (2019) A Visualization Tool to Investigate the Interplay of External and Internal Processes, in Design Computing and Cognition '18. Cham: Springer International Publishing, pp.669–686.
Voyer, D. et al. (2020) Sex Differences in Tests of Mental Rotation: Direct Manipulation of Strategies With Eye-Tracking, Journal of experimental psychology. Human perception and performance, 46(9), pp.871–889.
Zeman, A., Dewar, M. and Della Sala, S. (2015) Lives without imagery – Congenital aphantasia, Cortex, 73, pp.378-380.
Zeman, A. (2021) Blind Mind's Eye: People with aphantasia cannot visualize imagery, a trait that highlights the complexities of imagination and mental representation, American scientist, 109(2), p.110.