APPLIED TESTS OF ENGINEERING DESIGN SKILLS: VISUAL THINKING CHARACTERIZATION, TEST DEVELOPMENT AND VALIDATION

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ABSTRACT

A number of cognitive skills relevant to conceptual design have been previously identified: Divergent Thinking, Visual Thinking, Spatial Reasoning, Qualitative Reasoning and Problem Formulation. A battery of standardized test has been developed for these skills. We have already reported on the contents and rationale for divergent thinking test, as well as, on data collection and statistical analysis for it. This paper focuses similarly on the efforts related to the visual thinking and spatial reasoning in engineering context. It is designed to evaluate six measures: ***visual comprehension*** including ***perceptual speed, visual memory, visual synthesis mental image manipulation/ transformation, spatial reasoning*** *and* ***graphical expression/elaboration***. We discuss the theoretical basis of a comprehensive test for engineers, test composition, trial runs and computation of reliability measures. The alpha version was given to a small set of subjects to determine clarity of the questions and gauge difficulty level. The beta version was used for norming and test validation from over 300 samples, engineering students and a smaller number of practicing engineers. The test is shown to be reliable (Cronbach alpha less than .05 and only 2 eigenvalues greater than 1).

Keywords: ideation, visual thinking, engineering design skills, standardized tests, design cognition

1. INTRODUCTION

Academics and practitioners seem to have an awareness that good designers possess more than just vast domain knowledge; they have certain abilities that make them more effective in using that knowledge to structure ill-defined problems, construct fluid design spaces to facilitate fluency and flexibility of generating solutions and visualizing the detailed working of artifacts in their imagination. Although design skills are indirectly alluded to in design textbooks and curricula, there has not been a concerted effort to explicitly identify and measure them. In our ICED05 paper we identified and characterized a set of skills found in good engineering designers [1]. We also devised objective measures of these skills. We defined a skill as the cognitive ability to perform a task. Design skills were derived from observations of design tasks, as well as, from cognitive studies. We identified the following design skills: *Divergent thinking, convergent thinking, deductive, inductive and abductive reasoning, spatial reasoning, visual thinking, analogical reasoning, sketching,, qualitative reasoning, decision-framing and decision making, designing and conducting simulated or real experiments*. Not all of these are independent or unique skills; for example, there is an inexplicable relation between deductive reasoning and convergent thinking, between visual thinking and spatial reasoning. Pattern recognition and analogical reasoning may be interpreted in terms of physical, behavioral or linguistic context, thus being part of visual thinking, spatial reasoning or qualitative reasoning.

We are now developing standardized tests for a sub-set of these skills, those related particularly to conceptual design. Our team consists of an engineer, a cognitive psychologist, an educational psychologist and a psychometric consultant. We have so far developed and analyzed data from tests for Divergent thinking (DT) and Visual Thinking (VT) including Spatial Reasoning. Work on Qualitative Reasoning (QT) is in progress and future plans include tests for Problem Formulation (PF). Possible applications of these tests include evaluating students in design classes, forming of balanced design teams which possess skills necessary for a given project and evaluating the effectiveness of design courses and curricula.

Our ICED09 paper reported on the construction of the DT tests [2] and our ASME DTM paper [3] reports on DT results, data analysis and reliability studies. This paper focuses on development and validation of a comprehensive test for visual thinking and spatial reasoning for engineering design.

2. VISUAL THINKING (VT): THEORIES & MODELS

To understand the cognitive basis of visual thinking, one must consider the dimensions of visual experiences, the different types and levels of cognition that involve visualization, the underlying cognitive representation of visual information, and the neuroscience of visual cognition.

Qualities of Visual Images: In cognitive science, an *image* is a mental representation (like a code or a photograph) of an experience, and a visual image has certain qualities that distinguish the image from other types of representations, such as verbal or motor representations). The dimensions represented by visual images at the lower levels of cognition include physical features, such as spatial information, color, shape, and texture. In higher-order cognitive activities, such as those involved in problem solving, reasoning, or sketching, images might also include verbal information, motor codes, and abstract relations. Visual experience obviously has something to do with one's eyes, but it is also clear that visual experiences go far beyond what happens in the eye. Visual cognition includes perceptual experiences, maintaining and manipulating images in conscious working memory, retaining and retrieving visual information from memory, combining visual representations with other types of information such as verbal or abstract information, and solving problems, making inferences, discovering insights, and other types of higher-order cognition that are particularly relevant to design.

Visual Cognition: Visual thinking, or visual cognition, refers to seeing, and the ways that visual information is encoded, represented, organized, manipulated, transformed, and combined [4,5]. Retinal patterns are carried by the optic nerve, via the lateral geniculate nucleus, to the occipital lobe of the brain, *Area V1*, near the back of one's head. Individual neurons in the cortex of Area V1 called *feature detectors* respond to specific patterns of light, which are critical to object identification.

Perception refers to the organization and interpretation of sensory signals those results in a cognitive representation of what is seen. A neural path connects Area V1 to the parietal lobe of the cerebral cortex, the *dorsal stream*, which tracks an object and determines an understanding of *where* the object is [6]. An independent neural pathway connects Area V1 with the temporal lobe of the cerebral cortex. This *ventral stream* identifies *what* the object is, a process known as object recognition [6].

Visualization, which involves mental imagery, is a different activity than *seeing*, which is a perceptual modality. *Visual perception* of objects requires sensation of visual stimuli, and rich *perceptual images* that correspond rather directly to attributes of the physical stimuli they represent. These perceptual images endure for only a fraction of a second, during which time the cognitive system can extract a small amount of information for more enduring cognitive representations. A person can scan a perceptual image (if they can still see the object) and re-examine it to notice previously unobserved details. Visual mental images, in contrast, require no proximal stimulus; mental images can be constructed from material already memory, and they can be manipulated at will even with one's eyes closed. Visual mental images can be scanned and re-examined, but they are typically quite sketchy, containing very little in the way of complex detail. Mental images can be flexibly altered, manipulated, and combined, whereas perceptual images cannot. Research on visual cognition has repeatedly shown important similarities between perceptual and mental images (e.g., [7-9]), and cognitive neuro-scientific studies indicate that the two use the same parts of the brain (e.g., [10-11]).

Codes that Represent Visual Images: The *dual coding theory* [14] states that two distinctly different coding systems and two separate channels are used for verbal labels (words) and visual images; one's cognitive load in the same modality (visual or verbal) should interfere with performance because of shared cognitive resources, but if load is added in a different modality, performance should not suffer. There is overwhelming experimental evidence to support this theory from studies of perceptual imagery, studies of working memory and long-term (e.g., [11-14]).

The Visuospatial Sketchpad: Our capacity for maintaining information in short-term memory is quite limited, and without intervention, information endures in short-term memory for only about 20 or 30 seconds. These two limiting factors, short-term memory's limited capacity and brief duration, are important considerations, and can be supported by the cognitive mechanisms of rehearsal and chunking. Short-term, or working memory capacity is frequently cited as an important correlate of many forms of intellectual proficiency, ranging from self control to reading comprehension to problem solving ability (e.g., [15]). The working memory model developed by Baddeley [16], supported by considerable empirical data, includes a *central executive* buffer that makes decisions, directs attention, reasons, solves problems, and manipulates the information maintained by the slave buffers; three "slave" buffers: an *articulatory loop*, which can maintain a sequence of verbally coded syllables, an *episodic buffer*, which foregrounds information about previously experienced situations, and a *visuospatial sketchpad*, where visual images can be constructed and maintained. Because each of the buffers in working memory can maintain information independently of the other buffers, and because each buffer has a limited capacity, it is the case that interference is found only within a resource-limited buffer, and not between different buffers. Some people are able to make use of regularities and redundancies in compressing the information in visual displays, enabling them to maintain a greater load in visual working memory [17].

Mental Rotation: The most popularly used paradigm in studying visual imagery has been the mental rotation task. Participants are shown two figures, side-by-side; one is a standard figure, and the second is the comparison figure. The comparison figure is either the same configuration as the standard, or a mirror image, and the standard is always rotated in the plane of the test page. The participant is timed to see how long it takes to correctly respond "same" or "mirror-image," making mental rotation a chronometric measure. Mental rotation of 2D and 3D objects takes more time the greater the angle of rotation [18, 19], indicating that an analog code is used, because verbal descriptions of rotated images should take equal times, regardless of the degree of rotation [20]. Similar results have been found with chronometric studies if imagined visual scanning, rotation, and zooming in or out of a figure in a picture. Individual differences have been found on mental rotation speed [21,22]. These findings indicate that the mental rotation of images is an ability that represents an enduring trait of individuals.

Visual Long-Term Memory: An abundance of evidence supports the idea that visual coding can enhance long-term memory [23]; words one reads are likely to be encoded in memory with only a verbal code, whereas pictures are likely to be encoded with both verbal and pictorial codes; the double encoding ensures better memory retrieval. Whether visual images are useful for mnemonic techniques because images are information-rich, because images are more distinctive than words, or because visual images promote dual long-term memory codes, it is clear that the power of mnemonic imagery resides prominently in the usefulness of interacting visual images for encoding, and subsequently decoding new associations (e.g., [24,25]).

Combining Visual and Verbal Codes: Because memory has a limited capacity for maintaining mental images, people often represent visual objects as combinations of analog and verbal codes [26,27]. Visuospatial schemas combine visual, spatial, verbal, and abstract relational. A *cognitive map* is a type of visuospatial schema used to mentally represent an external environment, such as one's immediate surroundings. In general, cognitive maps represent three different types of geographic information, distance, shape, and relative position. These different types of information generally support each other, but systematic distortions can occur in cognitive maps because of verbal labels. A *mental model* is a schema that corresponds to the configuration of a dynamically changing or interacting system, such as a vacuum cleaner, a digestive system, or the solar system. Although visuospatial information is critically important for a mental model, that information is usually bound to abstract, verbal, and conceptual information.

Cognition & Sketching: A good way to examine schemas, cognitive maps, and mental models, is to have people sketch their own schemas. Conceptions of spaces vary across situations, and derive from combinations of both perceptions and actions associated with those spaces [28]. These mental concepts of various spaces are used for comprehension, perception, and action within the space. Sketching is a means of expressing or describing one's conception of a space. Sketching provides a medium that supplements and extends our visualization abilities [29]. If visuospatial information is sketched rather than visualized, it relieves the burden of cognitive resources necessary for constructing and using the space that is represented by the sketch, freeing up those cognitive resources for other tasks, such as development and refinement. Sketches, being visible, can be examined and reconsidered, and new properties and relations can be thereby discovered, including unintended properties [30,31]. Tversky & Suwa also point of that sketches can represent essential information better in the absence of distracting and irrelevant detail. Furthermore, abstract elements and relations, verbal labels, and even temporal sequences can be represented in sketches, making them critically important for communication, comprehension, inference, discovery, and insight [31].

3. VISUAL THINKING AND ENGINEERING DESIGN

Design researchers have looked at the role of sketching in creativity and design. McKim [32] studied the interaction between seeing, imagining and drawing, and ways in which they are related to design. Using protocol studies Ullman [33] found that during the design process 72% of the marks made on paper by designers were sketches; two thirds of these were freehand. Goldschmidt [34] studied the use of “serial sketching” in architectural design. It was observed that as sketching progresses, new shapes and relationships among shapes are created on paper, far beyond what was intended at the outset. Thus, sketches provide feedback to the sketcher in a way that other representations cannot provide. Larkin and Simon [35] have shown that sketches are very useful in problem solving because of their conciseness of representing data, compared to verbal descriptions. The relative spatial positions between different groups of data help the designer to *see* new relationships among groups of data, leading to insights about the design problem. Finding relationships between information stored in widely separated sentences is tedious, and the mind often misses relationships. Larkin & Simon [35] showed that problems represented by sketches require fewer computations and searches than problems represented by sentences. Sketches do not require that a figure be drawn to scale or exact dimensions. Since they are created quickly, sketches allow facile manipulation of ideas and are *graphic metaphors* for real objects. Since most sketches are not used for communication, a designer can use personal shorthand notations to represent symbolically pertinent information. Sketches act as gestalt; designers can *read off* from a sketch far more information than was invested in initially creating the sketch [32]. give access to mental images, figural or conceptual, that can trigger ideas for solving design problems [36]. Early design sketches are dense and ambiguous, affording reinterpretation in many different ways [30]. Sketching early in design gives meaningful hints that help define specific problem spaces where searches for a solution are likely to be productive [34]. Sketching is largely a mental process, thoughts are purged from the mind using a pencil and feedback enables the designer to refine and document the design [32]. Sketching reduces the demand on the short term memory, enhancing with this the stability of memory, and association can be more easily made through sketch data [32,37].

Although sketches have all the advantages described above, it has been observed that designers benefit to different degrees from the use of sketches. Larkin and Simon [35] state that sketches are of help only to those who know how to make full use of them, which comes with practice and experience. With more experience, designers learn to cultivate the dialogue to fully exploit its potential [38]. It has been found from protocol studies that experienced architects are better than students at reading abstract features and relationships from sketches [32].

A number of cognitive models have been proposed to explain the feedback loop between visual memory, perception, transformation and sketching [39,40, 41] . According to Verstijnen, [42], creative discovery is the result of a set of mental operations on a visual image. Through sketching, lateral transformations are facilitated, early fixations are prevented, and relationships are revealed.

Based on material in Sec2 2 and 3, we can say that there is strong theoretical and empirical evidence that Visual Thinking and Spatial Reasoning are an essential design skills, particularly in mechanical, industrial and architectural design.

4. VISUAL THINKING CRITERIA

From the foregoing analysis of cognitive models of visual thinking and a survey of existing tests of visual and spatial skills, we classified VT factors into six categories (Table 1):

Table 1: classification, definitions and indicators for measuring VT

VT Criteria	INDICATORS
Visual memory	Recalling object shapes, relationships, location, object attributes (color, texture, etc)
Visual comprehension	Object/feature recognition; understanding semantic relations; categorization; perceptual speed; image completion
Visual Transformation (mental image manipulation)	Affine transformations (rotation, reflection, scaling, etc); view transformation; color, texture, attribute transformation; cross-sections; 2D ⇔ 3D Transformation ; orthographic projection; layout re-arrangement
Visual, spatial reasoning	Motion simulation; analogical reasoning; induction; discovering patterns; foldouts; discovering inconsistencies; Part removal from assembly, Layout/arrangement in constrained space, Assembly/disassembly sequence
Visual synthesis	Generation of new objects; creating images from verbal description; synthesis of 3D object from 2D views; intersections
Visual expression	Drawing skills; quality of sketching; proportions; clarity of expression; embellishments such as shading

<u>Visual memory (VM)</u> skill engages analog and propositional encoding of visual, spatial, and potentially verbal representations of diagrams. When one first sees a diagram and represents that

pattern in long-term memory, the encoded representation can have multiple formats, including analog representations that map directly onto visual features, and verbal descriptions that represent conceptual relations among the encoded elements. The detail represented in analog encodings depends upon visual perception and attention, whereas the verbal codes depend upon one's ability to quickly notice conceptual information and relationships. Whereas long-term memory for analog detail is quite susceptible to forgetting caused by intervening time and experiences, memory for gist, which is stored in verbal or propositional formats, tends to be less susceptible to forgetting.

Visual comprehension(VC) is a form of higher order cognition that engages schemas, mental models, and sometimes, cognitive maps. These structures are learned, primarily via personal experience, and the accuracy and efficacy of these knowledge structures are developed and fine-tuned by careful feedback. Comprehension takes place as a type of perceptual pattern recognition in which visually perceived patterns are compared with learned patterns until some level of correspondence is found.

Mental Image Transformation, or Visual Transformation (VT), occurs as a function of visual perception and visual working memory. The same cognitive structures and processes engaged in mental rotation, one of the most well-researched visual phenomena, are likewise involved in mental image transformation. These include visual perception of test stimuli, visual working memory (to maintain test stimuli in a foregrounded state), and executive working memory (to execute various types of transformative operations, such as rotation, extension, or changes in relative size).

Spatial and visual reasoning (VR) are similar to other types of reasoning, such as analogical reasoning and inductive inference, except that the elements that are subjected manipulated in visual reasoning are holistic, analog forms that are "chunked" into manipulable units. Performance on visuospatial reasoning tasks depends on the ability to form visual chunks, as well as general reasoning skills.

In visual synthesis (VS), component visuospatial forms are held in visual working memory and manipulated similar to the image manipulation used in mental rotation or transformation. Following combinatorial play of these component elements, which is carried out by the executive functioning of the working memory system, a holistic form must be recognized. Thus, visual synthesis requires a blend of executive functioning and perceptual recognition, as well as visual working memory capacity.

Visual expression(VE), including sketching, involves visual cognition and also a coordination of perceptual, motoric, and working memory codes. That is, perceptual images and mental images must be represented and maintained in visual working memory, and that representation must be coordinated with the motor movements involved in drawing. Sketching and other visual expression can reveal schemas and mental models, and show the level of abstraction and errors in conceptual processing.

5. SURVEY OF STANDARD VISUAL & SPATIAL REASONING TESTS

A large number of cognitive tests for visual and spatial skills already exist. Some are designed to measure childhood development and some are for discovering abnormalities in individual, such as the Developmental Visual Perception (VP) test [43]. None are specific to engineering design. Each test focuses on some sub-set of visual cognition skills. An overview of these tests is given below.

The Mental Cutting Test (MCT) examines an individual's spatial visualization abilities [44]. It uses simple block shapes being cut by planes at an angle and asks the examinee to pick the cross-section shape that would result. There are two types of questions: ones that focus only on the cross-section shape and others that involve both the shape and size/proportions. In our classification, we categorize them into spatial reasoning and image manipulation/transformation. The Schnitte MCT is very similar [45]. The Rey Complex Figure Test (RCFT) consists of four separate tasks: Copying a figure, immediate recall, delayed recall (composed primarily of straight lines) and pattern recognition [46]. Whereas immediate recall of these complex figures depends a great deal on visual working memory capacity, and long-term memory for both gist (conceptual information) and visuospatial detail, delayed recall is highly susceptible to interference from intervening stimuli; this interference tends to diminish the level of detail one can recall, while leaving memory of gist representations relatively intact over time. A 2D figure consisting mostly of straight lines is used as the stimulus. One can see certain entity clusters that offer the potential of chunking. The pattern recognition tasks consists of 24 geometric figures, 12 of which contain geometric patterns found in the stimulus and 12 do not. For the first three exercises, scoring is based on accuracy and placement. We consider all these exercises as pertaining to visual memory. The Kit factor Referenced Cognitive Tests [47] covers six factors. In the first test, one needs to find "hidden" patterns, or pick out polygonal figures that have been buried inside extraneous information (Factor CF1). The second test MV is for visual memory and similar to RCFT pattern recognition exercise, except that it uses curved 2D shapes. The third factor P measures the speed with which one is able to pick out an identical simple figure from a set of similar figures. The fourth factor S is a mental rotation test for 2D figures about the normal axis (undefined rotation point). Factor VZ asks one to fit polygonal blocks together to form specified shapes, so it clearly corresponds to visual synthesis and mental rotations. The last factor is Figural Flexibility (XF) that involves matchstick puzzles, re-arranging matches in a 2D pattern to create specified patterns within some constraints. This involves visual comprehension and transformations. We do not consider this to be visual synthesis because the final object is already given. Vandenburg & Kuse Mental Rotations test VKR [48] contains 20 items in five sets of four visual stimuli. Each stimulus is a 3D figure; the responses are several variations of the same object that has been rotated through an unspecified axis. One needs to respond if each variation shown is the same as the stimulus. The Purdue Spatial Reasoning tests [49] are similar to exercises done in technical drawing courses. It includes paper folding exercises (development of 2D objects into 3D by bending along specified lines), viewing polyhedral objects from different directions, and rotations. The rotation exercises are harder than those discussed above as some involve rotating about multiple axes sequentially. Cube comparison tests involve rotating dice like cubes with inscriptions on each side [50]. Rotations may be around standard (intrinsic) axes or around task-defined axes. Another rotation test is the so-called “Arabic” figures [51] that uses 3D objects (balls arranged in tetrahedral formation) rotated about x,y,z axes.

Table 2 gives a summary of factors evaluated by visual/spatial tests we surveyed. None of the tests is comprehensive. Many are based on 2D problems. None test for visual expression and only part of one test involves visual synthesis. We found that most engineering students get perfect scores on these, making them poor candidates to assess design skills.

Table 2: Survey of existing Visual/Spatial Tests

Test surveyed	MCT	RCFT	VKR	Purdue	Cube	Arabic	DvpVP	Kit factor ref tasks					
								CF1	MV	P	S	VZ	XF
Visual memory		X							X				
Visual comp							X*	X		X			X
Image Transfrm	X		X	X	X	X					X	X	X
Spatial reasoning	X												
Visual synthesis												X	
Visual expression													
Dimensionality	3D	2D	3D	3D	3D	2-3D	2D	2D	2D	2D	2D	2D	2D

* perceptual speed measured by response time

6. VT TEST CONSTRUCTION

We set out to develop a comprehensive test of visual skills in engineering design context. The goal was to construct a test that would cover all six VT skills, be appropriate for engineering students as early as the sophomore year, and one that could be administered in 60-90 minutes. In order to carry out validation studies later, it is necessary to test each factor with multiple items on the test. For efficiency, it was also important to consider the possibility of designing questions that could measure more than one skill independently; for example, visual expression and visual memory, or visual expression and transformation. Additional guidelines used in test construction were to keep the questions free of technical drawing conventions and to test with three levels of questions: easy, moderate, difficult in order to create differentiation between individuals. Ideally different mediums should be used in measuring each skill (text, sketch, physical model, computer rendering). For practical reasons, it was decided that at this time only a paper-and-pencil test was to be used.

An alpha version of the test was created to get feedback from trials about the clarity, difficulty level and time allocated to each exercise. The alpha version contained 12 modules. Except for 3 visual memory modules, each module consisted of three similar questions arranged in the order easy, moderate, difficult. The rationale was that the vast majority of engineering sophomores could answer the first question in each module with ease, while the second one might present challenges to the average person and the third could be solved only by outstanding visual thinkers. The instructions given at the start clearly specified the six factors that were being tested.

Table 3 gives a summary of question types in each module, the number of exercises in each and the time allocation and the factors being tested. Each module shows clearly the combined time allowed for answering all questions in that module (a clock icon with the number).

Table 3: SUMMARY of VT Test: alpha version

Module # > _	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
Content >	image manip	Anal-ogy	Inter-secn	Shadow	Affne trnsf	Motion sim	Xsec	Txt-to--image	2D-3D	Fold-out	Drg	Recall	
#Exercises >	2	4	4	3	3	3	2	3	3	3	1	3	34
Time allocation (min**)** >	3	3	3	3	3	5	4	6	6	5	10	10	62
Category													
Visual memory												**X**	3
Visual comp		**X**							x			**X**	9
Image Trnsf.				**X**	**X**	x	x						11
Spatial reasoning	**X**	x	x			**X**	**X**		**X**	**X**			17
Visual synthesis			**X**					**X**	**X**				10
Visual expression				x			**X**	x	x		**X**	x	13
Dimensionality	2,3D	2D	3D	3D	2D-3D	3D	3D	3D	3D	3D			

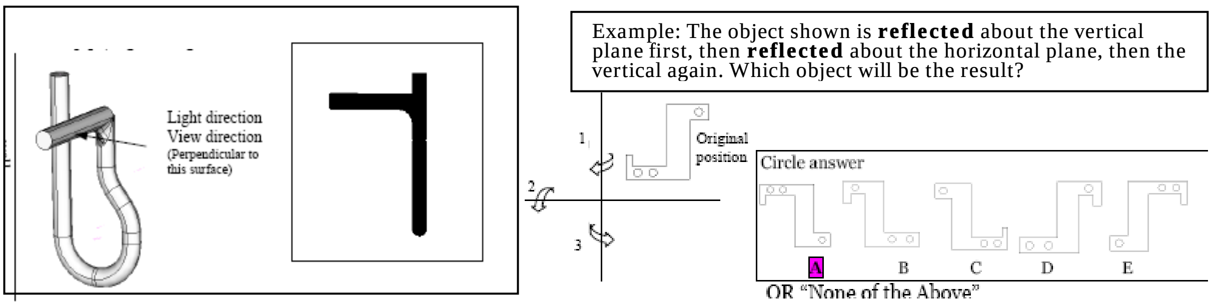
The three memory recall questions (Module 12) are not given at once, but rather evenly spaced in between other questions. In each of the three, a figure is shown for 1, 2 or 3 minutes, and then the subject is asked to work through a few unrelated exercises. Then the subject is asked to sketch what was shown earlier. The three exercises are graduated in difficulty by the number, variety and complexity of the constituent features. Each exercise offers opportunities for chunking related features to enhance memory capacity, a skill that visual thinkers use. Thus, the VM items are testing delayed recall in the presence of distractions.

Module 1 (M1) tests VR. The subject is given a series of operations to construct a mental image of an object, without drawing, and then to "look" at the image formed to answer some questions related to certain characteristics of that object. The easy exercise is 2D in nature, while the harder one is 3D.

M2 tests visual comprehension by discovery of patterns of changes between series of similar objects. By visual analogy, one is expected to predict the next member of the series. There are multiple questions in the module arranged from easy to difficult.

M3 tests visual synthesis of objects formed by the intersection of two 3D objects. Although visual reasoning is also involved, the primary process is piecing together intersection curves to create a new 3D object. The easy questions in this module are based on polyhedral objects; the harder ones on curved objects.

Technical drawings are based on multiple views or orthographic projections. Some VT tests surveyed (e.g., Purdue test) also include such exercises. It was important to include this type of exercise but to make them independent of technical drawing conventions, so that those without such education are not at a disadvantage. We devised an exercise (M4) where students are asked to draw the outline of an object's shadow when a light is placed at some orientation in front of an object and a screen on the opposite side behind the object. Again, easy, moderate and difficult versions were devised with different complexity objects and variations in light source/screen locations. The exercise demands affine transformations, so it tests VT factor. Since students are asked to sketch the answers it is possible to also grade their drawing skills (VE). M5 tests VT in a different manner, by incorporating several types of affine transformations: rotations, translations, reflections and scaling combinations. The traditional tests have focused on rotations only but all types of transformations are needed in visual thinking and related to engineering design. Most modules are accompanied by one solved example to make the instructions clear, as shown in Figure 1.



(a) shadow exercises in M4 *(b) transformation sequences in M5*

Figure 1: Illustrative examples for M4 and M5

Using simple mechanisms, M6 tests visual reasoning in an engineering setting. The artifacts involve motion of different kinds and answers are presented as multiple choices.

M7 involves generation of cross-section views along specified cutting planes. Unlike MCT, the objects are realistic engineering artifacts and not simple polyhedra. They contain multiple features, including protrusions and holes. Not only can VR be evaluated from this exercise but also VE since students are asked to give the answers as scaled sketches (outlines of cut surfaces on cutting plane).

M8 involves text-to-image transformation. An assembly of objects is described in words, not only the shapes but also sizes and cross-sections. One needs to mentally “fabricate” and assemble the objects and then to express their mental image as a proportioned sketch, complete with dimension notes. Students are not allowed to draw any of the intermediate states. Again, the exercises are arranged easy-difficult. This is the most direct measure of visual synthesis.

M9 is the opposite of M4; instead of going from a 3D drawing to 2D views from different directions, it goes from 2D to 3D. That is, two or more views are given and the 3D shape needs to be derived. This module measures both VC and VE, independently. M10 is a classic technical drawing exercise: a 3D hollow object is given and one needs to determine how to create it by cutting and bending a contiguous piece of sheet metal (or cutting and folding paper). There can be multiple correct answers. It involves visual reasoning. M11 assesses free hand sketching skills. Students can choose from three different assignments: automotive, architectural, or art sculpture.

The alpha test was given to a small number of experienced designers to get feedback for improvements. As a result, some of the questions were modified. It was also realized that the time allocations were not sufficient in some cases, even for experienced designers. Several of the difficult questions from some modules were dropped. The free hand exercise is important but if the test is to be completed in a typical class period, it was not realistic to expect good results, so M11 was replaced by a Tangram exercise for VS. The modified test was used in beta trials for use in statistical analysis.

7. SCORING

Grading criteria were developed for each module to measure the factors listed in Table 4. The total number of points allocated to each question in a module were based on relative difficulty. For example, in M1 the easy question carried 10 points and the harder 20 points for VR. Weighting was also used across modules for the same factor. For example, M3 is weighted 3 times M1 for VR.

Table 4: Overall distribution of scores for each module and factor(Beta version)

Q#	**1**	**2**	**3**	**4**		**12a**	**5**	**6**	**12b**	**7**		**8**		**9**	**10**	**11**
	Image manip	Visual anlgy	3D intsc	shadows		Delay recall	Afin trnsf	Mot-ion	Delay recall	Cross-secs		Text-to-figs		2D-3D	Fold-out	Tan-grams
	VR	**VC**	**VR**	**VT**	**VE**	**VM**	**VT**	**VR**	**VM**	**VR**	**VE**	**VS**	**VE**	**VE**	**VR**	**VS**
MAX	**30**	**90**	**60**	**25**	**10**	**10**	**50**	**30**	**10**	**10**	**5**	**20**	**10**	**10**	**30**	**10**
i-1	11	59	60	19	7.5	7.8	10	30	3	10	4	15.7	7	5	20.5	6
i-2	16	40	60	21.5	7.5	5.4	30	30	8	0	0	17.1	5	5	26.6	10
i-n																

	AGGREGATES						**NORMALIZED**					
	ΣVM	**ΣVC**	**ΣVT**	**ΣVR**	**ΣVS**	**ΣVE**	**VM**	**VC**	**VT**	**VR**	**VS**	**VE**
MAX	**20**	**75**	**75**	**150**	**30**	**35**	**10**	**10**	**10**	**10**	**10**	**10**
SAMPLE1	10.8	50	29	139	21.7	23.5	5.4	6.7	3.9	9.3	7.2	6.7
SAMPLE2	13.4	46.6	51.5	125	27.1	17.5	6.7	6.2	6.9	8.3	9.0	5.0
…..												

M1 has unique right answers (numerical) and is straightforward to grade. In M2 there are multiple independent attributes that need to be discovered in the patterns; some are more obvious than others; consequently worth different number of points. A sample basis is presented below along with the relative weighting of the four questions in the same module:

Scoring criteria
No. of keys = 4: 2 pt
Arrangement: 90 deg = 2 pt
Key shape: rectang = 4 pt
Key size: smaller than last = 2 pt
Sub-Total (max 10, min 0)

Copy subtotals for each part below and multiply by weights

Module#2	Q	VC		
		Wt	pts	score
graphical analogy	a	1		
	b	2		
	c	3		
	d	3		
Total				

2) VC=a+2b+3c+3d = ____

M3 has four multiple choice questions (3D intersections) with weights corresponding to the level of difficulty. Therefore, grading is quite straightforward. M4 (shadows) has many aspects that are independently graded for VT factor, as depicted in Table 5. The same responses can be used to evaluate drawing skills (VE factor) by looking at proportions, line straightness and embellishments, such as shading.

Table 5.Scoring criteria for Visual Transformation and Visual Expression for module M4

VT scoring criteria	score		VE Scoring criteria	score
Frame: vert 1 pt; rect=1pt			Proportions: 5	
Brkt: horz=1 pt; rect=1 pt			Line straightness: 2	
Drum: horz=1 pt;			Shading: 2	
shaft: horz=1 pt; rect=1 pt			**Sub-Total** (max 10, min 1)	
Placement = 2				
Symmetry=1				
VT2 Sub-Total (max 10, min 0)				

M5 involves affine transformation sequences and has only one correct answer for each multiple point set. The only scoring issue is to determine relative weights for the VT score for each question. The same applies to M6 for VR scoring.

M7 responses (cross-sections) are scored feature by feature, based on the existence, size, orientation and placement of the feature. Points are deducted for extraneous features that are not part of the correct cross-sections. The same responses in this module can be independently used to evaluate VE skills in the same way as described earlier for M4. Scoring of M8 and M9 is similar to M7, that is feature-by-feature, although M8 measures synthesis of mental images of assemblies from textual descriptions (VS factor) and M9 measures VC factor in 2D to 3D transformation. In both cases, because responses are as sketches, the VE factor can also be evaluated.

M10 (foldouts) measures VR factor. It is scored based on how close the formed shape will be to the desired shape, the number of missing or extraneous faces and the number of correct/incorrect bend lines. M11 (Tangram) has only one correct answer, so it is straightforward to evaluate the VS score.

Scoring sheets have been created showing the correct answers, the above scoring criteria, and a way to record and audit scoring by different graders. This tentatively ensures consistency across graders, which of course must be verified through statistical analysis. As shown in Table 5, the total points for each of the six factors obtained from all of the modules are different. Therefore, it is necessary to normalize all to a common value (10 in our case).

8. RESULTS & STATISTICAL ANALYSIS

During trial runs the test was progressively refined. The beta version was given to over 300 engineering students and a smaller number of industry designers. A Factor Analysis was done in PASW (formerly SPSS) involving 17 items contained 12 Modules. Table 6 shows correlations for every sub-skill from every Module. Two different views of these statistics are shown in Tables 7 and 8. Table 7 shows consistency of measuring the same skill from different modules and Table 8 shows correlations across skills for normed totals. Table 7 reveals that our test is fairly consitent for VR and VE; it is a bit less for VT, weak for VC and inconsistent for VM.

In comparing the correlation of all the questions to each other, almost all of them are related at an Cronbach alpha of .01 or .05 level except M12a(VM). Taking this a step further, in the analysis of the VM data, 12a and 12b are actually negatively correlated, which means we might need to replace 12a. On the totals, all of the factors are highly correlated to each other EXCEPT for the VC items, which do not have a significant relationship to four of the six factors. VR is the highest related factor to the overall score. The highest related factor to the overall score is Visual Reasoning; lowest is Visual Comprehension. The Factor Analysis reveals that there are possibly two eigenvalues above 1.0. Another validation of its consistency. The scree plot is shown in Figure 3.

Table 6: Correlations across every item measured

	M1-VR	M2-VC	M3-VR	M4-VT	M4-VE	M12a-VM	M5-VT	M6-VR	M12b-VM	M7-VR	M7-VE	M8-VS	M8-VE	M9-VE	M9-VC	M10-VR	M11-VS
M1-VR	1.00	0.25	0.41	0.37	0.32	0.19	0.27	0.36	0.30	0.42	0.29	0.25	0.37	0.40	0.34	0.37	0.38
M2-VC	0.25	1.00	0.13	0.30	0.25	0.16	0.13	0.34	0.01	0.32	0.32	0.20	0.24	0.33	0.24	0.21	0.21
M3-VR	0.41	0.13	1.00	0.30	0.23	0.01	0.07	0.34	0.16	0.40	0.44	0.02	0.28	0.34	0.32	0.39	0.30
M4-VT	0.37	0.30	0.30	1.00	0.54	0.05	0.16	0.29	0.24	0.50	0.35	0.22	0.31	0.46	0.40	0.42	0.25
M4-VE	0.32	0.25	0.23	0.54	1.00	0.18	0.24	0.29	0.17	0.49	0.35	0.12	0.34	0.48	0.38	0.43	0.26
M12-VM	0.19	0.16	0.01	0.05	0.18	1.00	0.19	0.12	-0.01	0.10	0.16	0.01	0.05	-0.03	-0.09	0.06	0.15
M5-VT	0.27	0.13	0.07	0.16	0.24	0.19	1.00	0.29	0.29	0.18	0.20	0.27	0.13	0.16	0.16	0.19	0.08
M6-VR	0.36	0.34	0.34	0.29	0.29	0.12	0.29	1.00	0.22	0.37	0.36	0.24	0.19	0.43	0.34	0.46	0.29
M12-VM	0.30	0.01	0.16	0.24	0.17	-0.01	0.29	0.22	1.00	0.18	0.15	0.15	0.17	0.31	0.28	0.22	0.31
M7-VR	0.42	0.32	0.40	0.50	0.49	0.10	0.18	0.37	0.18	1.00	0.65	0.26	0.32	0.40	0.35	0.47	0.36
M7-VE	0.29	0.32	0.44	0.35	0.35	0.16	0.20	0.36	0.15	0.65	1.00	0.16	0.33	0.44	0.36	0.46	0.27
M8-VS	0.25	0.20	0.02	0.22	0.12	0.01	0.27	0.24	0.15	0.26	0.16	1.00	0.55	0.24	0.39	0.26	0.27
M8-VE	0.37	0.24	0.28	0.31	0.34	0.05	0.13	0.19	0.17	0.32	0.33	0.55	1.00	0.40	0.36	0.28	0.41
M9-VE	0.40	0.33	0.34	0.46	0.48	-0.03	0.16	0.43	0.31	0.40	0.44	0.24	0.40	1.00	0.69	0.44	0.36
M9-VC	0.34	0.24	0.32	0.40	0.38	-0.09	0.16	0.34	0.28	0.35	0.36	0.39	0.36	0.69	1.00	0.50	0.26
M10-VR	0.37	0.21	0.39	0.42	0.43	0.06	0.19	0.46	0.22	0.47	0.46	0.26	0.28	0.44	0.50	1.00	0.19
M11-VS	0.38	0.21	0.30	0.25	0.26	0.15	0.08	0.29	0.31	0.36	0.27	0.27	0.41	0.36	0.26	0.19	1.00

Table 7: Correlations across modules for the same sub-skill

	M1-VR	M3-VR	M6-VR	M7-VR	M10-VR
M1-VR	1.00	0.41	0.36	0.42	0.37
M3-VR	0.41	1.00	0.34	0.40	0.39
M6-VR	0.36	0.34	1.00	0.37	0.46
M7-VR	0.42	0.40	0.37	1.00	0.47
M10-VR	0.37	0.39	0.46	0.47	1.00

	M4-VE	M7-VE	M8-VE	M9-VE
M4-VE	1.00	0.35	0.34	0.48
M7-VE	0.35	1.00	0.33	0.44
M8-VE	0.34	0.33	1.00	0.40
M9-VE	0.48	0.44	0.40	1.00

	M4-VT	M5-VT
M4-VT	1.00	0.16
M5-VT	0.16	1.00

	M2-VC	M9-VC
M2-VC	1.00	0.24
M9-VC	0.24	1.00

	M8-VS	M11-VS
M8-VS	1.00	0.27
M11-VS	0.27	1.00

	M12a-VM	M12b-VM
M12-VM	1.00	-0.01
M12-VM	-0.01	1.00

Table 8: Correlation matrix

	VM	**VC**	**VT**	**VR**	**VS**	**VE**	**OVR**
VM	1.0	0.15	0.39	0.21	0.28	0.25	0.53
VC		1.0	0.29	0.46	0.41	0.61	0.71
VT			1.0	0.33	0.31	0.4	0.67
VR				1.0	0.39	0.66	0.77
VS					1.0	0.53	0.7
VE						1.0	0.81
OVR							1.0

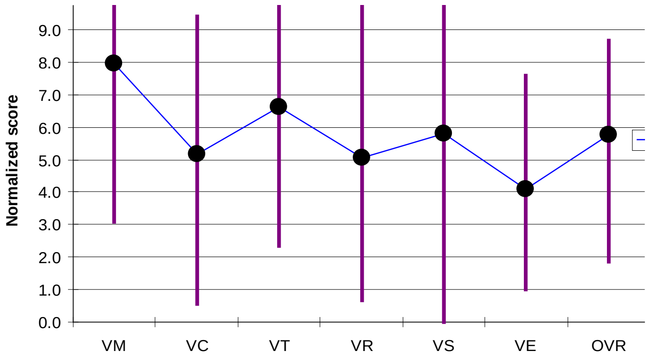


Figure 2: Score ranges and Norms

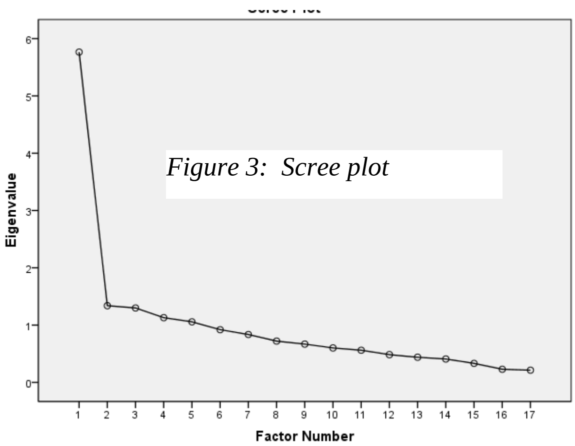


Figure 3: Scree plot

9. DISCUSSION

From theoretical and empirical studies of visual cognition, perception and memory, we have identified six basic types of spatial and visual skills relevant to engineering design. A comprehensive test for all skills has been developed, put through trial runs and statistically validated. The strong correlations and reduction to 2 factors indicate that the data collected may be sufficient. The tests goes beyond technical drawing classic problems and developmental tests by Psychologists. The test is now ready to be used by design educators for additional trials (http://asudesign.eas.asu.edu/testsportal/index.php) and possibly for assessing students, as well, as, visual thinking related curricula.

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