Synesthesia and Engineering Design: How Synesthetes Differ in Their Approach and
Understanding of Engineering Systems and Their Design

Submitted by

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An Introduction to Synesthesia, the Medial Temporal Lobe, and V4

What is Synesthesia?

Synesthesia is a sensory modality in which an individual's response to a stimulus (an inducer) triggers an additional perceptual experience (the concurrent) [1]. A synesthete might, for example, listen to a song and, simultaneously, see colors related to the theme or tone of the music. These responses are automatic, involuntary and consistent, often remaining unchanged over long stretches of time [2]. After being reported in scientific papers from the late 19th century as little more than a curiosity, the scientific community largely ignored synesthesia until the mid-1970s [3]. By the early 2000s, neuroscientists and psychologists had begun to perform empirical research on the condition [3]. It was at this point that synesthesia began to be regarded as a genuine condition [3]. Of the myriad of types of synesthesia that started to be studied, most of the available data are on grapheme-color synesthesia. When a grapheme-color synesthete looks at an achromatic grapheme (i.e. a written symbol; usually a Latin letter or Arabic numeral in Western studies), the person perceives that grapheme as if it were filled in by or highlighted with a color.

Being a relatively new condition of interest, several viable neuropsychological mechanisms for grapheme-color synesthesia have emerged over the last two decades. In 2001, Hubbard and Ramachandran introduced their cross-activation theory [4]. In its original form, this theory proposed that additional, unnecessary neurons in the lateral occipitotemporal gyrus (fusiform gyrus) linking the 'visual word form area' (VWFA) and the 'visual area 4' (V4) color processing area failed to degrade[1] in early childhood [3]. Further, Hubbard and Ramachandran

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[1] During the first year or so of life, the brain produces an excess of neurons in several areas of the brain [5]. As a child develops, unused neural connections degrade [5].

suggested that synesthesia has a genetic origin [3]. 10 years later, Hubbard et al. proposed an amendment to their cross-activation theory, which they term the 'cascaded cross-activation model' [3]. This model retains much of what was proposed in the original cross-activation formulation, but also incorporates recent research positing that grapheme and word processing contains a hierarchy [3]. In accordance with this, they write that features, rather than letters, are recognized first [3]. Hence, they now believe that there are inhibitory and excitatory connections both within the grapheme-recognition level and between the grapheme-recognition level and other levels above and below it in the hierarchy [3]. In the same year that the original formulation of the cross-activation theory was published, Grossenbacher and Lovelace advanced the disinhibited feedback model for synesthesia [1]. They noticed that areas of the brain which receive signals from multiple pathways feedback onto these same pathways [1]. For a non-synesthete, Grossenbacher and Lovelace surmise that signals from concurrent sources is inhibited. A synesthete, on the other hand, lacks this inhibitory process for certain stimuli, resulting in complementary perceptions [1]. Additionally, the re-entrant model was put forth by Smilek et al. in 2001 [6]. This model is something of a hybrid between the disinhibited feedback model and the cross-activation model [3]. In the re-entrant model, a stimulus activates neurons that are sensitive to that stimulus, which leads to an individual perceiving that stimulus [3]. The act of perceiving that stimulus initiates feedback onto the previously induced neurons in addition to concurrent neurons [3]. The originally induced neurons also feedback onto the concurrent neurons [3]. This feedback, then, actuates a synesthete's additional perception event [3].

The Visual Cortex and V4

Delving into each of the theories above necessitates an understanding of color, letter, shape representation, and interpretation in the brain as deduced from imaging, brain

morphometry, anatomy, electroencephalographic, and magnetoencephalographic studies.

Neuroscientists divide the hemispheres of the brain into four lobes (see Figure 1). In order of

size: the frontal lobe, the temporal lobe, the parietal lobe, and the occipital lobe [7]. The frontal

lobe, as its name suggests, is the most anterior of the lobes [7]. Dorsal and posterior to the frontal

lobe is the parietal lobe, and the temporal lobe is ventral and posterior to the frontal lobe [7]. The

occipital lobe is posterior to both the temporal and parietal lobes [7]. The visual cortex, which is
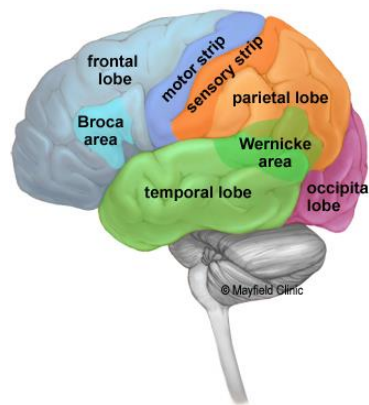

Figure 1 [7]. Brain with frontal, temporal, parietal and occipital lobes labeled.

located in the medial occipital lobe, is responsible for processing visual information from the

retinas [5]. Signals first leave the retinas through the optic nerves before entering the optic

chiasm [5]. Information from the left sides of the left and right eyes travel on the left optic tract,

while information from the right sides of the left and right eyes travel along the right optic tract

[5]. The optic tracts eventually synapse with the dorsal lateral geniculate nucleus in the thalamus

before entering the visual cortex via the optic radiation [5]. VSignals initially make their way

into the primary visual cortex (V1) in the calcarine fissure area [5]. Information from the macula

terminates at the posterior end of the calcarine fissure area; information moves farther away from

this point if it is further from the macula [5]. The secondary visual areas of the visual cortex

surround V1 [5]. It is this part of the occipital lobe that is responsible for evaluating the visual

information sent to V1 [5]. Visual areas under the 'secondary visual area' classification include

Brodmann's area 18 (V2), V3, and, V4 [5]. Visual information follows two major pathways: the

fast 'position' and 'motion' pathway and the accurate color pathway [5]. The first of these

pathways determines an object's position in three-dimensional space, its gross form, and whether

it is moving [5]. Information that travels along this pathway crosses the dorsal border of the

occipital lobe into the posterior parietal lobe. The accurate color pathway is responsible for

detailed analysis of visual information [5]. Information carried along this pathway moves from

the ventral occipital lobe to the posterior temporal lobe [5].

Of the secondary visual areas, V4 has proved to be one of the most enigmatic to

neuroscientists [8]. As first demonstrated in rhesus monkeys, V4 contains cells that are

responsive to wavelength, implying that V4 might play a vital role in color processing [8, 9].

Nevertheless, human V4 also has neurons which are sensitive to an object's orientation and

position in space, texture, form, and motion [9]. Moreover, human V4's location in the occipital

lobe has never been conclusively determined. The V4v/V8, the hV4/VO, and the V4v/V4d

models are competing retinotopic maps for the location of human V4 [8]. Note that 'V4v' refers

to the ventral portion of V4, 'V4d' indicates the dorsal subset of V4, 'hV4' specifies that this

mapping of V4 includes a hemifield map, and 'VO' refers to two additional hemifield maps

around the ventral occipital fovea [8, 10]. The V4v/V8 map, as proposed by Hadjikhani et al.,

positions V4v as being proximal to V3. Hadjjikhani et al. identify a new visual area, 'visual area

8' (V8), adjacent to V4v. They conclude that V8, and not V4, is responsible for color processing

[8]. The hV4/VO model, on the other hand, replaces V8 and V4v with hV4, VO-1, and VO-2 [8].

Proponents of the V4v/V4d model state that the lower vertical meridian[2], which is included in the

hV4 model, is not present in what they call V4v [8]. In addition, they claim that another portion

of V4 is located adjacent to dorsal V3 [8].

Grapheme-Color Synesthesia and V4

Using magnetoencephalography (MEG), Hubbard et al. observed significantly greater

activity in V4 in synesthetes than in controls [3, 12]. This observation is perhaps not unexpected;

depending on one's positioning of V4, V4 either has or is adjacent to neurons that are receptive

to color. As stated previously, V4 also contains neurons associated with shape. It is not too far of

a stretch to suggest that V4 might be associated with recognizing and interpreting letters.

Importantly, the number of synesthetes ($n = 4$) and controls ($n = 4$) in this study was

exceptionally small [12]. Small sample sizes increase the likelihood of sampling error and,

therefore, may not generalize to the larger population. In their functional magnetic resonance

imaging (fMRI) and surface-based morphometry study, Jäncke et al. found increased cortical

volume, thickness, and surface areas in the fusiform gyrus [13]. In the posterior fusiform gyrus,

which is approximately around what Jäncke et al. deem 'V4α,' these differences were more

pronounced than in the other areas of the fusiform gyrus [13]. Hupé et al. counter these claims.

In their study, they found that none of the previously-used boundaries for V4 experienced

heightened levels of activation [14]. Furthermore, they found that this result was constant for all

grapheme-color synesthetes, regardless of the strength of their synesthesia (i.e. whether they

simply associate colors with graphemes and see these colors in their mind's eye or actually

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[2] One's visual field may be broken into two axes called 'meridians' [11]. The axis stretching from the top of one's visual field to the bottom is called the 'vertical meridian,' and the axis moving from left to right is termed the 'horizontal meridian' [11]. The origin of these two axes is the dividing point between the upper and lower vertical meridians as well as the left and right horizontal meridians [11].

perceive that they are seeing colors) [14]. Interestingly, Hupé et al. used a combination of actual graphemes and 'pseudo-graphemes' based on the Latin alphabet and Arabic numerals to see if the synesthetic response was still active if the synesthete were to associate a 'pseudo-grapheme' with a grapheme [14]. Hupé and Dojat also point out that studies reporting structural differences at or near the visual cortex were inconsistent [15]. For example, they identify two studies by
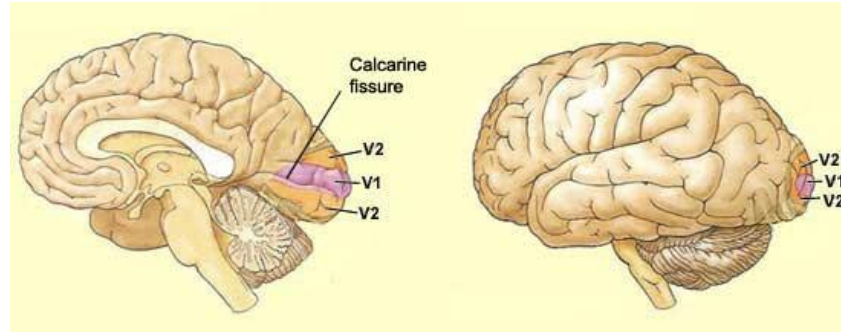

Figure 2 [16]. Location of V1, V2, and the calcarine fissure as seen from a cross-section of the brain (left) and the entire brain (right).

Rouw and Shulte in which reported differences in the fusiform gyrus (which happens to be near the visual cortex), identified in their 2007 study, were contradicted by their larger 2010 study [15]. Hupé and Dojat also state that two out of nine studies using fMRI found a significant difference in retinotopically-defined V4 in synesthetes exposed to graphemes than non-synesthetes, suggesting that further studies must be completed to conclusively link any structural component of the brain to grapheme-color synesthesia [15].
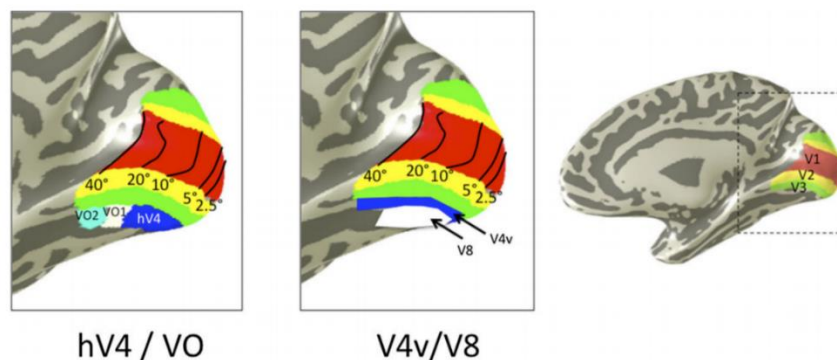

Figure 3 [8]. Visual comparison between the V4v/V8 and hV4/VO models.

The Medial Temporal Lobe and its Synaptic Links to V4 and the Visual Cortex

Broadly speaking, the medial temporal lobe is responsible for declarative memory [17]. Declarative memory is defined by Squire, Stark, and Clark to be, "…conscious memory for facts and events…" [17]. The medial temporal lobe consists of four primary components: the hippocampal region, the entorhinal cortex, the perirhinal cortex, and the parahippocampal cortex [17]. The entorhinal cortex, the perirhinal cortex, and the parahippocampal cortex together make up the parahippocampal gyrus [17]. Processing in the medial temporal lobe follows a specific hierarchy [17]. Information from unimodal association areas (association areas which receive one type of sensory input) and polymodal association areas (association areas which receive multiple types of sensory input) in the frontal, temporal, and parietal lobes in addition to the retrosplenial cortex feeds into the perirhinal and parahippocampal cortices [17, 18]. The perirhinal and parahippocampal cortices then supply information to the entorhinal cortex, which sends its association information to the hippocampal region [17, 18]. The hippocampal region may be further subdivided into four sections with its own hierarchy [17]. In order from lowest to highest: the dentate gyrus, the CA fields, and the subicular complex [17]. The entorhinal cortex supplies each of these subcomponents with its processing output [17, 18]. Moreover, the two lower subregions feed forward to the subregion that is one higher (e.g. the dentate gyrus' output feeds into the CA fields) [17, 18]. After reaching the subicular complex, information travels back to the entorhinal cortex, allowing information to move forward and backward between the entorhinal cortex and the hippocampal region [17, 18]. This is not unique to the entorhinal cortex and the hippocampal region; rather, adjacent levels in the first hierarchy discussed also communicate with one another [17, 18, 19]. As an example of this, note that the perirhinal cortex

supplies information to the unimodal and polymodal association areas and vice versa [17, 18, 19].

Recently, it has been proposed that the medial temporal lobe assists the visual cortex in visual processing, although this claim is controversial [20]. This proposal is part of what is known as the two-streams hypothesis. In addition, synaptic inputs have been demonstrated to exist between the medial temporal lobe and V4 in macaques [21]. Ninomiya et al. found that the CA fields send significant amounts of information through the entorhinal cortex to V4 [21]. They also demonstrated that there are alternative pathways between the CA fields and V4 which
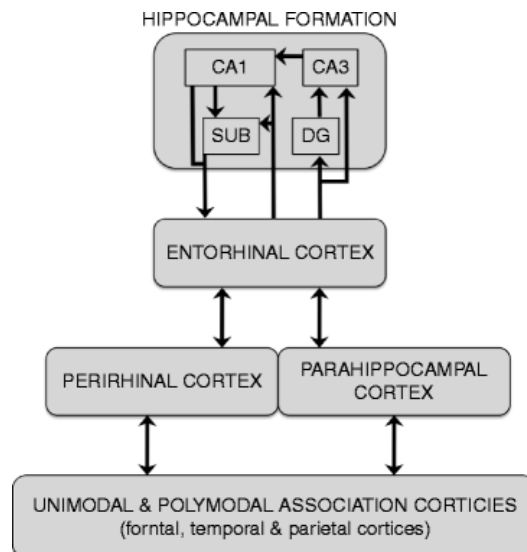

Figure 4 [19]. A schematic of the flow of information in the medial temporal lobe.

do not involve the entorhinal cortex [21]. Ninomiya et al. additionally note that the parahippocampal cortex is connected to V4 [21]. Connections between the visual cortex and the medial temporal lobe have also been noticed by Córdova et al., who showed that the parahippocampal cortex is coupled with attention to scenery and the perirhinal cortex is partnered with facial attention [22].

The Medial Temporal Lobe and Problem-Solving

Episodic memory is a subcategory of declarative memory. Episodic memory stems from a single event [17]. Examples of episodic memory include remembering one's birthday and the emotions that one associates with having celebrated it. As previously stated, the medial temporal lobe is responsible for declarative memory [17]. It seems to follow, then, that even those with small hippocampal lesions have pronounced difficulty with learning about a single event [17]. At least one study has determined the importance of episodic memory in solving open-ended social problems [23]. Sheldon et al. recruited those with temporal lobe epilepsy (TLE), older adults, and younger adults, provided them with the beginning (the 'problem statement') and end ('problem resolution') of several social situations, and asked them to create a story connecting the two [23]. Each new contribution to the story was classified as either a 'relevant mean,' an 'irrelevant mean,' or a 'no mean' [23]. Relevant means were defined to be solutions that move the participant in the direction of the problem resolution [23]. To be counted as a relevant mean, responses must be within the context of the problem statement [23]. Irrelevant means, on the other hand, do not bring the participant to the problem resolution, but are within the context of the problem statement [23]. No means do not move the participant's story toward the problem resolution and are outside of the bounds of the problem statement [23]. Furthermore, Sheldon et al. recorded whether a detail was 'internal' or 'external.' Internal details are those which are '…isolated to the event described,' while external details are not [23]. As an example, if one's story is about moving into a new neighborhood, an internal detail would be describing how well-kept the neighbors' houses are, while an external detail would be what one thought or still thinks of the neighbors' houses [23]. Sheldon et al. believe that episodic memory and the number of relevant means that one can provide across each story share a causal relationship [23]. Moreover,

they also write that the number of internal details is associated with episodic memory [23]. It was found that participants with TLE recorded significantly fewer relevant means and internal details than older adults [23]. Similar results held when the number of relevant means was normalized by the total number of means [23]. The number of relevant means were found to positively correlate with the number of internal details provided as well [23]. In a second experiment, older adults' responses were compared with younger adults' [23]. Like the first experiment, older adults provided significantly fewer relevant means and internal details than younger adults [23]. Normalizing the number of relevant means produced the same results as in the previous experiment [23]. Once again, Sheldon et al. recorded that there was a positive correlation between the number of relevant means given and the number of internal details proffered [23]. If one supplies more relevant means and internal details, they are judged to have solved the social problem more effectively [23]. Relevant means and internal details are also measures of episodic memory [23]. TLE is associated with a loss of CA1 and CA3 neurons in the hippocampus [24]. Hippocampal degradation is a natural part of the aging process, although much milder in scale than in those with TLE [23]. It follows that the state of one's hippocampus corresponds to one's performance on open-ended social problems [23].

Engineering Design and Synesthesia

Hypotheses

Engineering design is analytical, open-ended, and often complemented by visual interpretation of words and images. Both semantic[3] and episodic memory certainly play significant roles in engineering exercises. As an example, suppose that an engineer is designing a

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[3] Semantic memory is a subcategory of declarative memory and relates to repeated actions and general world knowledge [17, 25]. For example, remembering how to multiply two numbers together calls upon semantic memory.

gas turbine that can be modeled by the Brayton cycle. The engineer must, of course, have a working knowledge of the equations, pressure – specific volume (*P-v*), and temperature – specific entropy (*T-s*) diagrams, and must know the working fluid that the Brayton cycle is modeled with. All of these necessitate semantic memory. Additionally, an experienced engineer might be able to draw upon previous experiences to avoid prior pitfalls and other difficulties. In this instance, the engineer uses their episodic memory. As stated previously, the medial temporal lobe is generally associated with declarative memory. Hence, it is not too far of a stretch to say that the medial temporal lobe is especially important when solving engineering design problems.

To the best of my knowledge, the neuroscientific literature has not yet reached a consensus on the connections between human V4 and the medial temporal lobe. In macaques, however, there is at least one study showing that there are links between the medial temporal lobe and V4 (recall that Ninomiya et al. have demonstrated that the CA fields in the hippocampus send significant amounts of information to V4 through the entorhinal cortex) [21]. Even if this finding cannot be replicated in humans, there remains considerable support for the cross-activation theory and, thus, connections between V4 and the fusiform gyrus, which, in turn, is located directly adjacent to the parahippocampal gyrus. In Hubbard et al.'s review article, they emphasized that there is considerable support for their cross-activation theory from a diverse set of studies, including: functional neuroimaging studies, diffusion tensor imaging, voxel-based morphometry, and EEG and MEG studies [3]. At the very least, there is some evidence that there is heightened activation in V4 in synesthetes when they are provided a grapheme stimulus than in controls [12]. Furthermore, there appears to be more structural connectivity in the inferior temporal cortex in synesthetes compared with non-synesthetes [2]. The inferior temporal cortex is vitally important for visual object recognition [25]. It has also

been shown to be connected with V1, V2, V3, and V4 [25]. Additionally, Jäncke et al. have found structural differences in the part of the fusiform gyrus that is closest to V4α in synesthetes [13]. This finding lends additional support to the cross-activation theory and may indicate that there is a greater number of neural connections between the fusiform gyrus and V4 in synesthetes.

If grapheme-color synesthetes do indeed have structural differences in and around V4 or if there are demonstrable connections between V4 and the medial temporal lobe, then, because the medial temporal lobe is responsible for episodic memory, a grapheme-color synesthete may show some differences in how they store and apply episodic memory. As previously mentioned, a prior study demonstrated that those with episodic memory deficits performed worse when asked to solve open-ended social problems when compared with controls [23]. I attempt to determine whether this result generalizes to solving simple, visual engineering design problems. To ensure that these problems draw upon episodic memory, they must consist of relatively familiar items: pulley systems, piping systems, trusses, etc. I propose three hypotheses:

1. Grapheme-color synesthetes will show differences in performance on tests of episodic memory when compared to controls, perhaps due to structural differences in and around V4 and their impacts on the medial temporal lobe. In particular, I suggest that synesthetes will perform better than controls due to a greater numbers of neural connections between the areas adjacent to the medial temporal lobe and the color processing area.

2. Grapheme-color synesthetes will be more accurate than non-synesthetes on a visual engineering design test. I believe that synesthetes may have an easier time connecting past, one-time events to engineering design problems when visually-intuitive

diagrams are supplied. In accordance with the two-streams hypothesis, I also believe that having a greater number of neural connections between the visual cortices and the medial temporal lobe will make grapheme-color synesthetes better at object and shape recognition. I believe that this may, in turn, lead to improvements in diagram interpretation. This hypothesis also rests on experimental findings suggesting a greater number of neural connections between the fusiform gyrus and V4.

3. Grapheme-color synesthetes will display differences in how they interpret and use diagrams. Synesthetes have performed modestly better on tests of creativity compared with controls [26]. I anticipate novel problem-solving techniques and explanations of thought processes from grapheme-color synesthetes. I also believe that these responses will diverge from those given by non-synesthetes.

This study addresses the second and third hypotheses only. I believe that testing the first hypothesis would require an additional test and suspect that this will decrease the survey response rate.

<p align="center">*Materials and Methods*</p>

Dr. Pandey and I created a short, 11-question online test for participants to take. In all recruitment materials, participants were provided a link to the online test. Grapheme-color synesthetes were recruited from the Synesthesia List, an online e-mail forum that connects researchers, interested adults, and synesthetes with one another. Synesthetes will also be recruited from synesthesia groups on Facebook. Controls will be recruited from a mass e-mail addressed to all Honors College students at Oakland University. Participants were instructed to take the survey only if they are 18 years of age or older. All participants read and agreed with Oakland University's informed consent form and were required to speak English fluently. Every

question in the engineering design test is meant to be solved visually, although we did not require participants to do so. We did this to elicit an array of responses to test the third hypothesis.

Those interested in volunteering were presented with two survey options and could choose between them. Participants could choose to take or send their Synesthesia Battery[4] [27] results to the research team or could opt to self-report. The reasons for this were largely pragmatic; the Synesthesia Battery website was in the process of migrating to a new domain, and the test results were not being recorded at an acceptable frequency. Participants then moved onto an approximately 30-minute engineering design question test. At the beginning of this part of the test, respondents were instructed to provide information as to their academic interests or career field (e.g. whether they were majoring or working in the humanities, the natural sciences, engineering, etc.). The engineering design question test may be broken into two parts: a section requiring a participant to visualize a scenario being described in written text (non-diagram portion), and a section based on imagining how a provided diagram might move when subjected to a force or a stimulus of some sort (diagram portion). There were two questions in the non-diagram portion of the test and nine questions in the diagram portion. Each question in the non-diagram portion contained two sub-questions, one being multiple-choice and the other being short response. The multiple-choice sub-question asked for an interpretation of the question, while the short response portion asked for the participant's thought process. The diagram portion of the test varied in how its questions were formatted. Some questions in this section were

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[4] The Synesthesia Battery test verifies whether an individual claiming to be a synesthete is, in fact, a synesthete. Released to the public in 2007, the Synesthesia Battery compiles questions from questionnaires used by other researchers and combines these with short, Adobe Flash-based matching tests.

multiple choice while others were solely short-response. Two questions were similar in layout to the non-diagram portion; i.e. they asked a participant to select from a series of choices and then asked them to detail how they came up with their response. In contrast with the non-diagram portion, two questions simply asked one to select a response without justification. Three questions requested participants to describe how a diagram might look if it were subjected to one or more external forces. The remaining questions simply required yes/no responses. Some questions in this section had multiple correct answers. At the end of the test, participants were instructed to rate how confident they were in their responses on a scale from 0-10 (with 10 being the highest). For more information on the engineering design questions themselves, see Figures
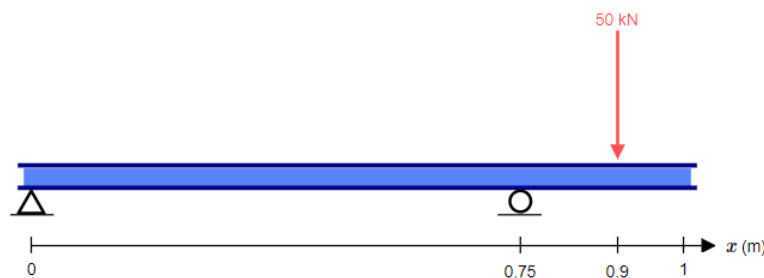
Figure 5. A diagram from the engineering design question survey. Respondents are asked to estimate the maximal point of deflection (either upwards or downwards).
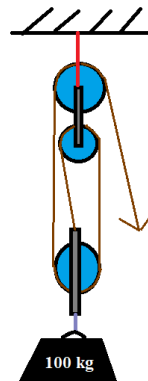
Figure 6. A diagram from the engineering design question survey. Participants are asked to determine whether the red rope or the brown rope is most likely to break.
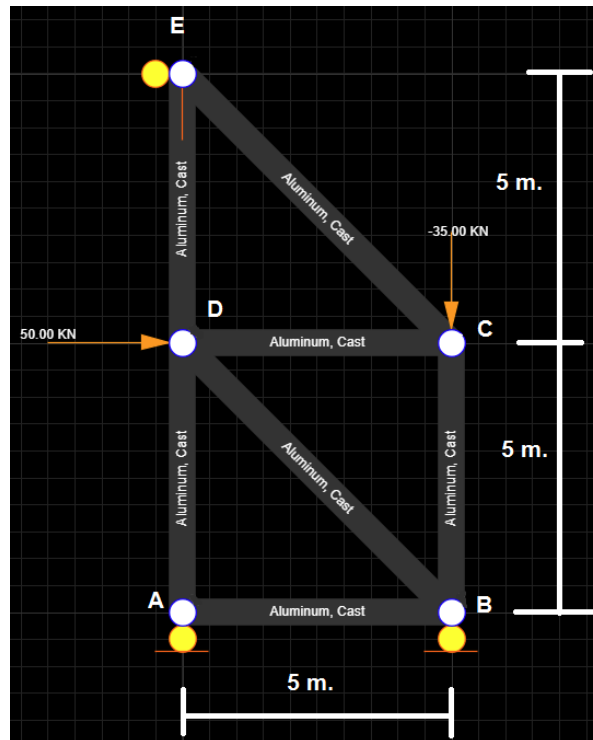
5, 6, and 7, Appendix A, and Appendix B.

Figure 7. A diagram from the engineering design question survey. Participants are asked which truss member is most likely to break when subjected to a force at joints D and C. Respondents were also instructed to describe how they arrived at their answer. Corrected from original survey

Depending on the number of responses and the diversity of the responses, Dr. Pandey and I will identify four different groups for comparison: engineers with synesthesia, engineers without synesthesia, non-engineers with synesthesia, and non-engineers without synesthesia. By doing so, we can determine whether having an engineering background or having synesthesia is most significant when solving visual engineering design problems.

Preliminary Results

At the time of writing, the survey has not been sent to controls or posted on Facebook. Therefore, the only respondents at this time are those from the Synesthesia List. Of those who

took and finished the survey ($n = 11$), 10 identified themselves as synesthetes and 1 did not. Table 1 summarizes the career information of all of the participants so far. All 10 synesthetes indicated that they took the Synesthesia Battery, but only 1 supplied their results to the research team. Career choices varied considerably and were relatively even across the board. 3 individuals recorded that they were either majoring or working in the fine arts. This was the maximum number of responses for one field. 2 participants indicated that they were working in the natural sciences and in the humanities, respectively. Other selected careers included business, health sciences/medicine, and the social sciences.

Table 1. Number of participants reporting one of several career fields.

Career/Major:	Number of Respondents:
Natural Sciences	2
Social Sciences	1
Formal Sciences	0
Engineering	0
Health Sciences/Medicine	1
Fine Arts	3
Humanities	2
Education	0
Business	1
Other/Not Specifically Indicated	1

Before continuing, I preface any analysis with a brief discussion on statistical power. In the proceeding sections, I will perform several balanced (an approximation) one-way analysis of variance (ANOVA) hypothesis tests and t-tests (with unequal variance and sample sizes). Note that, when running a one-way balanced ANOVA test on 10 groups (each group contains responses from individuals in a particular career field/field of study) with a moderate effect size of 0.25 at a significance level of 0.05, for one to achieve a power (i.e. the probability of rejecting

the null hypothesis given that it is false [28]) of 0.8[5], there would need to be 26 respondents in each group. For the current amount of data, the power of this ANOVA test will be very low. With a moderate effect size, the number of respondents in each group would need to be 64 if one were to perform a *t*-test with equal variances (an approximation). Increasing the sample size will increase the power of both of these tests. Therefore, there is a considerable chance that there is a significant difference that the null hypothesis in all of the following analyses will fail to be rejected, especially with the current number of participants. Hence, these results merely show how I will approach the data when more people respond to my survey.

Responses to the non-diagram portion of the engineering design question test were inconclusive. Participants who are studying or working in the fine arts performed better on the non-diagram portion than all other the other career categories with a mean score of 4.33 out of 6. This difference, however, was not found to be significantly different from any of the other sample means at the 0.05 significance level ($p = 0.077$, $F = 4.74$). Since only one individual identified themselves as a non-synesthete, it would be exceptionally premature to compare synesthetes' responses on this portion of the test to non-synesthetes'. In this section, respondents were asked how they arrived at their answer for one question (see Question 11 in Appendix A). Most individuals noted that they had seen jet engines on airplanes before and that this influenced their answer. This was a much more common response for participants whose background did not focus on the natural and health sciences. Surprisingly, some participants gave somewhat technical reasons for their choices. One individual discussed compression and thrust in jet engines and noted that compressing more air inside the engine will produce more thrust. Another

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[5] A significance level of 0.05 and a power of 0.8 are most often used in social scientific literature.

participant attempted to use the concepts of work and energy to arrive at their answer. It is worth

noting that these respondents' backgrounds are in the natural and health sciences. For a summary

of participants' scores on this portion of the test, see Table 2. Note that because some groups

only had one representative, the sample variance for those groups could not be computed. As a

result, variances are not recorded in Table 2.

Like with the non-diagram portion, results from the diagram portion of the test were

inconclusive. Those working in the natural sciences recorded the highest mean score on this

portion of the test, averaging 7 out of a possible 11. Similar to the non-diagram portion, the null

hypothesis was unable to be rejected (i.e. that all of the population mean scores for each

career/field of study were the same) ($p = 0.64$, $F = 0.75$). For more information on average

scores broken down by career/field of study, see Table 2. It is likely that a majority of

participants guessed for most or all of the questions in this section. Responses to the beam

deflection problems (Questions 20, 22, and 24 in Appendix A) showed that some participants did

not know what beam deflections were and showed that respondents were frustrated with the test.

In addition, some participants did not know what a truss was and, therefore, did not know where

to start with either of the truss problems. Respondents did, however, respond more positively to

problems that were readily related to a participants' prior experiences. For instance, Questions

13 and 14 asked for one to determine whether the longitudinal or circumferential portion of a

pipe would break if water were to freeze inside of it. Those that answered this question correctly

stated that they had experience taking care of pipes to prevent them from breaking or had seen a

pipe break in the circumferential direction before.

I now turn my attention to determining whether there is a significant difference in overall

mean score between those in the natural sciences and those who are not. Performing a Welch's *t-*

test on the data demonstrates that the observed differences do not reach significance at the 0.05 significance level ($p = 0.516$, $t = 0.933$). Once again, then, I fail to reject the null hypothesis that the population mean scores for these two groups are the same.

I would like to reiterate once again that participants found the survey to be extremely difficult. At the end of the survey, participants indicated how confident they were in their answers on a scale from 0-10, with 10 being the highest. Only 2 participants selected a number above 5, and 7 chose either a 0 or a 1. This, combined with some of the qualitative responses, suggests that most of the results so far were simply random guesses and were not visualized as intended.

Table 2. A summary of participants' results on the engineering design question test.

Career/Field of Study:	Non-Diagram Section Mean Score:	Diagram Section Mean Score:	Overall Mean Score:
Natural Sciences	4	7	11
Social Sciences	4	6	10
Health Sciences/Medicine	1	5	7
Fine Arts	4.33	3.67	8
Humanities	4	4	5
Business	2	2	6
Other/Not Indicated	2	6	8

Preliminary Conclusions

Ultimately, it is far too early to make any conclusions as to whether synesthetes solve visual engineering design problems better than their non-synesthetic peers or if their interpretations and approaches to engineering design problems are more novel or creative than those given by other individuals. To properly test my second and third hypotheses, I believe that the engineering design survey will need to be reworked and simplified. Rather than focus on complex engineering problems involving at least a cursory understanding of statics and dynamics, I propose using problems involving simple machines or elementary logic. Simple

machines are sometimes introduced in elementary or middle school. Elementary logic problems

are generally approachable for an average person because they require relatively simple

problem-solving techniques. Moreover, I strongly believe that they are straightforward enough

for anyone, even those without a background in the natural sciences, formal sciences, or

engineering to understand. In doing so, I also hope to appeal to participants' episodic memory.

While not particularly illuminating, these results certainly show the need to make a survey

intuitive so that participants do not become frustrated or overwhelmed.

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Appendices

Appendix A: Initial Distributed Survey

English ▼

Informed Consent

Q1.

Information Sheet for an Exempt Survey Research

Synesthesia and Engineering Design: How Synesthetes Differ in Their Approach and Understanding of Engineering

Systems

Introduction

You are being asked to be in a research study that is being done by Spencer Morris under the direction of Dr. Vijitashwa Pandey, the faculty adviser for this project. Dr. Pandey is an assistant professor in the Industrial and Systems Engineering Department at Oakland University.

Your decision to participate in this study is voluntary. You can choose to stop your participation at any time or skip any part of the study if you are not comfortable. Your decision will not affect your present or future relationship with Oakland University, the researcher, the Industrial and Systems Engineering Department, or the Honors College. If you are a student or employee at Oakland University, your decision about participation will not affect your grades or employment status.

What is the purpose of this study?

The purpose of this research study is to determine if there is a difference between synesthetes (with and without a background in STEM) and non-synesthetes (with and without a background in STEM) in how they approach and solve engineering design problems.

Who can participate in this study?

You are being asked to participate in the study because you are 18 years of age or older and are interested in solving a set of simple engineering design questions.

What do I have to do?

You will have the option of taking an online 40-minute survey and will be required to take a second, 20-minute survey. The first survey is optional. If you strongly believe that you have or do not have synesthesia, you may self-report your synesthesia status rather than take this survey. This survey will ask you to associate a color with one or more black-and-white symbols. You will then have to match a series of black-and-white symbols to a color as fast as you can. If the test determines that you have synesthesia, you may be asked an

additional set of questions asking you about your visualizations of textual descriptions of events and medical history. These sections are optional to complete. This first survey will be completed on the Synesthesia Battery website. To complete this survey, you will have to create an account and add the provided e-mail address to share your results with the researchers. Note that you will see a second consent form from the Baylor College of Medicine at the beginning of this survey.

The next survey is required. The second survey will ask you for answers to engineering design problems. Some of the questions in the second survey will ask for a brief (1-3 sentence) explanation of your approach to solving a problem.

Are there any risks to me?

For this study, the potential risks are those associated with disclosing one's status as a synesthete or a non-synesthete. This may be uncomfortable to some. There may also be a risk that someone who is not part of this research may accidentally see your personal information. We will try to make sure that this does not happen by keeping your research records as confidential as possible. When the results of this research are published or presented at conferences, no information will be included that personally identifies you.

Are there any benefits to me?

Although there may be no direct benefits to you, the results of this study may benefit others in the future.

Will I receive anything for participating?

You will not receive anything for participating in this survey.

What if I want to stop participating in this study?

If you want to stop participating, close your browser before clicking 'submit.' If you click 'submit,' it will not be possible to stop participating.

Who can I contact if I have questions about this study?

You may contact Spencer Morris (e-mail address: swmorris@oakland.edu; phone number: +1 (248) 971-8769) or his faculty adviser, Dr. Vijitashwa Pandey (e-mail address: pandey2@oakland.edu; phone number: +1 (248) 370-4044), if you have questions about this study.

For questions regarding your rights as a participant in human subject research, you may contact the Oakland University Institutional Review Board, 248-370-4898.

FOR IRB USE ONLY

This form was approved by the Oakland University Institutional Review Board on 02/27/2019 under IRBNet # 1357896.

Synesthesia Battery Redirection, Part 1

Q2. Have you taken a test on the Synesthesia Battery (www.synesthete.org/index.php) website

before?

○ Yes.
○ No.

If 'No' Instructions

Q3.
**Please note that this survey is optional. If you are interested in seeing whether or
not you have synesthesia, you may take this test. If you strongly believe that you
have or do not have synesthesia, you may skip this survey and indicate your
synesthesia status on the next page.**

The following link will take you to the Synesthesia Battery website, a site which tests whether or

not one has synesthesia: http://www.synesthete.org/index.php

To take a test and have your answers recorded, you will need an e-mail address and be willing to

create an account on the website linked above.

Please see my original website for steps on how to set up an account, have your answers sent to

our research team, and how to take the Color-Picker test:

https://sites.google.com/oakland.edu/spencermorris/synesthesia-research

When you have finished the Synesthesia Battery test, please click the two sideways chevron

arrows on the lower right-hand corner of your screen.

If 'Yes' Instructions

Q4.

If you would like to share your results with the research team, please log in to your account and

enter the following information when prompted to send your results to a researcher:

Researcher's Email Address: synesthesiaresearch2@gmail.com

Researcher's Name: Spencer Morris

Sending your results is optional. When you are finished, continue with the survey by clicking on

the two sideways chevron arrows on the lower left-hand corner of your screen.

Engineering Design Problem Portion Instructions

Q5. You will now take a short survey testing your engineering intuition. Before beginning,

please answer the following questions:

Q6. If you chose to take the Synesthesia Battery test, please enter the e-mail address that you

used to take the Synesthesia Battery (used to match Synesthesia Battery results only).

[   ]

Q7. Do you have synesthesia?

○ Yes.

○ No.

Q8. Which of the following best describes your schooling (if you are a student) or career (if you

are not a student) background?

○ Natural Sciences (e.g. Physics, Chemistry, Biology, etc.)

○ Social Sciences (e.g. Psychology, Sociology, Economics, Linguistics, etc.)

○ Formal Sciences (e.g. Mathematics and Statistics, Computer Science, etc.)

○ Engineering

○ Health Sciences / Medicine

○ Humanities (e.g. Law, Languages, History, English, etc.)

○ Fine Arts, including Art Education

○ Business

○ Education

○ [   ] Other (Please Specify)

Engineering Design Questions - Visualization Section

Q9. Imagine several horizontal pipes are transporting oil in parallel at a constant velocity. You

are tasked with creating a piping system that maximizes the amount of oil transported per unit

time. Indicate how you believe the oil transportation rate (volumetric flow rate) would be affected if the each of the following properties were increased:

	How would the oil transportation rate be affected if the properties on the left side were increased?		
	Increase	Decrease	Stay the Same
Pressure Drop Along the Length of the Pipe	O	O	O
Pipe Radius	O	O	O
Pipe Length	O	O	O
Viscosity of the Oil	O	O	O

Q10.

Broadly speaking, turbojet engines used in larger airplanes follow the Brayton cycle to produce thrust. The Brayton cycle is a thermodynamic cycle that uses ideal gas air as its working fluid. The first step in the Brayton cycle is that air enters the turbojet engine and is heavily compressed. Following compression, the air enters a combustor, is mixed with jet fuel, and burned. The air then passes through a turbine, producing shaft work (energy) to power the compressor and electronic equipment inside the plane. Air then exits the engine at a fast velocity and re-enters the atmosphere. The cycle is completed when the air leaving the turbojet engine mixes with the atmospheric air and cools off before re-entering the plane.

In your judgment, which inlet and outlet geometries would make the most sense for a turbojet engine?

O An inlet with a small radius and an outlet with a large radius.
O An inlet with a large radius and an outlet with a small radius.
O An inlet with a small radius and an outlet with a small radius.
O An inlet with a large radius and an outlet with a large radius.

Q11. For the previous question, describe your thought process in 1-3 sentences.

Longitudinal axis

Circumferential direction
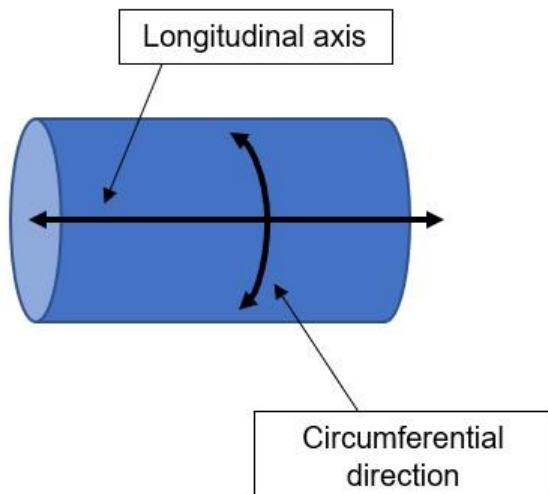
Q13.

In the winter months, water in pipes is at risk of freezing. Unlike most liquids, water expands when it freezes and therefore exerts a greater pressure on the walls than it would in its liquid state. Assume that the cylinder in the picture above is a section of a thin-walled pipe which normally contains liquid water. If the water in the pipe freezes and the pressure is significant enough to rupture the pipe, would you think that the rupture would be along the longitudinal axis, or would it be in the circumferential direction?

○ Longitudinal axis.
○ Circumferential direction.

Q14. For the previous question, explain your thought process below.
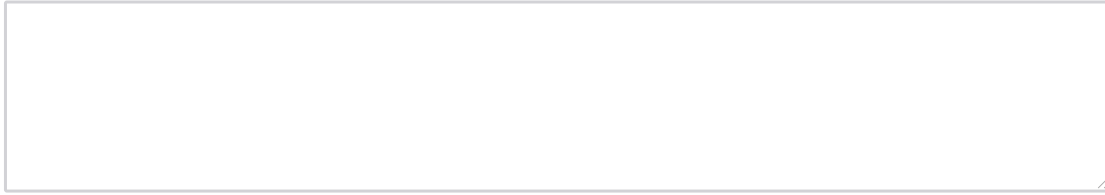
Engineering Design Questions - Picture Interpretation Section
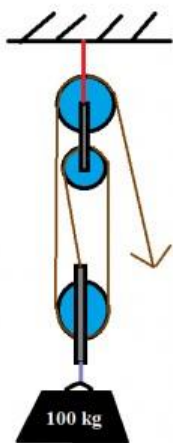
Q16. Which one of the ropes in the pulley system above would you expect to break first?

Assume that the rope attached to the weight is sturdy and cannot break. Also, assume that the

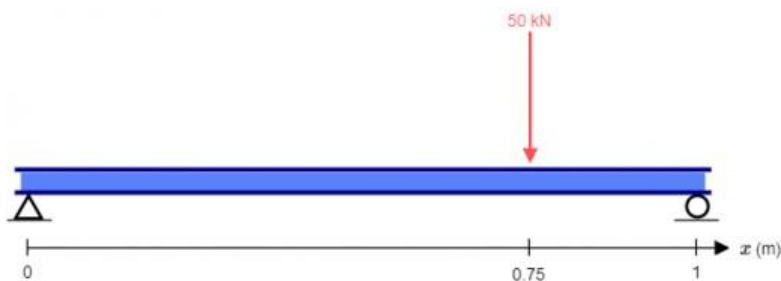ropes have no mass and friction effects are negligible.
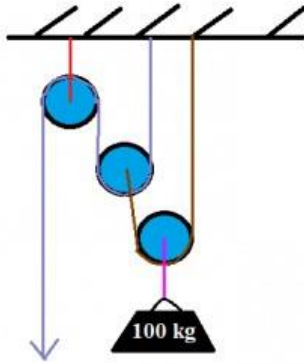
○ Brown rope.
○ Red rope.

Q18. Which one of the ropes in the pulley system above would you expect to break first?

Assume that the rope attached to the weight is sturdy and cannot break. Also, assume that the

ropes have no mass and friction effects are negligible.

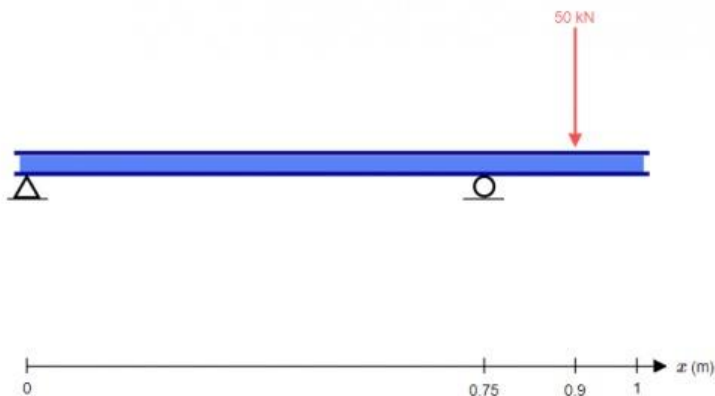○ Brown rope.
○ Red rope.
○ Purple rope.

Q20.

Consider the aluminum beam in the image above. The beam is supported by a pinned connection

(i.e. allowed to rotate at the point) at its leftmost end and a roller (i.e. only vertical movements

restricted at this point) at the other. A downward, concentrated load of 50 kilonewtons (kN - a

unit of force) is applied 0.75 meters (m) along the beam. Where would you think the maximal

deflection point would be?
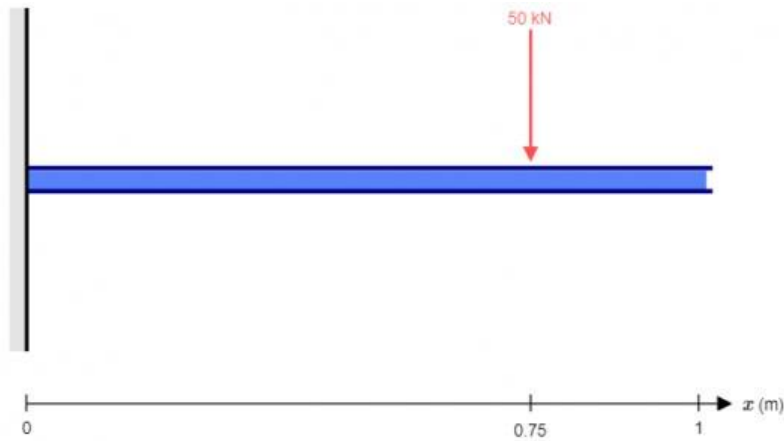
Q22.

How would the maximal deflection point change if the beam were a cantilever attached at the left

(see the figure above)? Note that a cantilever is a beam that is anchored at one position and free

at the other. For the figure used in Part A, the pin would be replaced by a rigid support (e.g. a

wall) and the roller would be removed without replacement.

Q24. Consider the aluminum beam in the image above. The beam is supported by a pinned

connection (i.e. allowed to rotate at the point) at its leftmost end and a roller at the 0.75 m mark.

A downward, concentrated load of 50 kilonewtons (kN - a unit of force) is applied 0.9 meters

(m) along the beam. Where would you think the maximal deflection point would be?
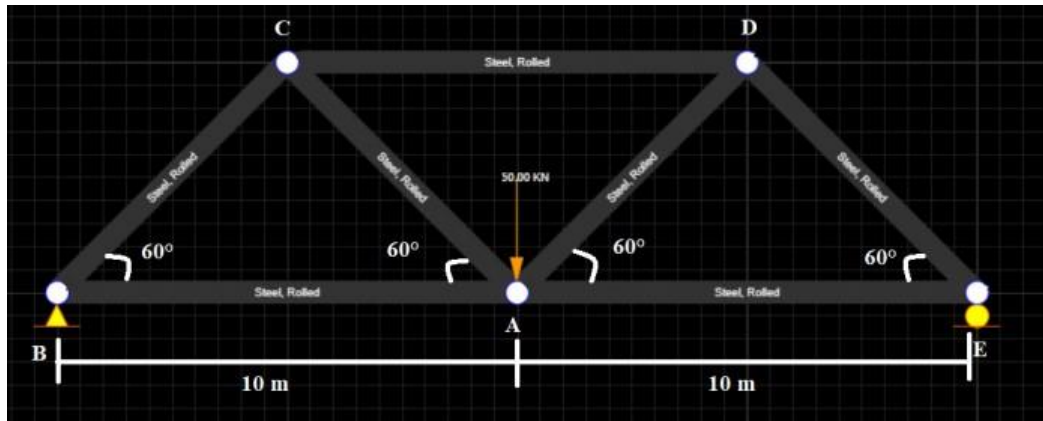
Q26. If each of the members of the truss have the same allowable stress values in tension and

compression, in which member would you expect the truss to break first? Note that the yellow

triangle indicates a pinned connection (i.e. rotations are allowed at that point) and the yellow

circle indicates a roller (i.e. the truss can move side-to-side at this point).

○ Member AB.
○ Member AE.
○ Member AC.
○ Member AD.
○ Member BC.
○ Member CD.
○ Member DE.

Q27. Describe what you would think the truss would look like after breaking in 1-3 sentences.
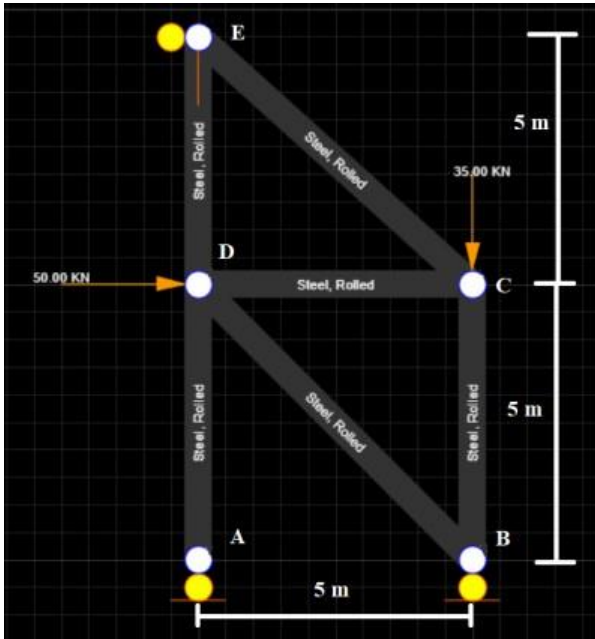
Q29. If each of the members of the truss have the same allowable stress values in tension and

compression, in which member would you expect the truss to break first? Note that the yellow

circles are rollers (i.e. the truss is allowed to move side-to-side at these points). While not shown

on the diagram, suppose that there is a member AB as well.

O Member AD
O Member AB
O Member BC
O Member BD
O Member CE
O Member CD
O Member DE

Q30. Describe what you would think the truss would look like after breaking in 1-3 sentences.

Q31. The animated GIF below demonstrates the operation of a simple slider-crank mechanism. As the crank moves in a circle, the crank's angular motion pushes the slider backwards and forwards.
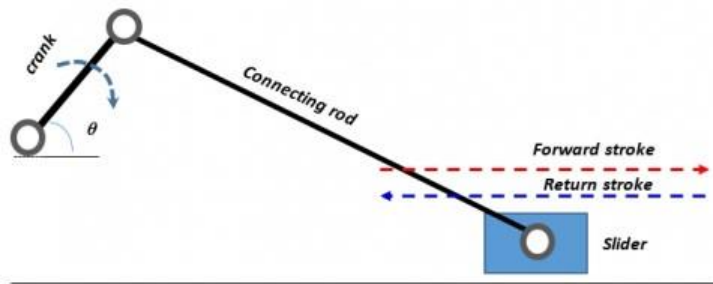
Source: https://commons.wikimedia.org/wiki/File:Slider-Crank_Mechanism.gif
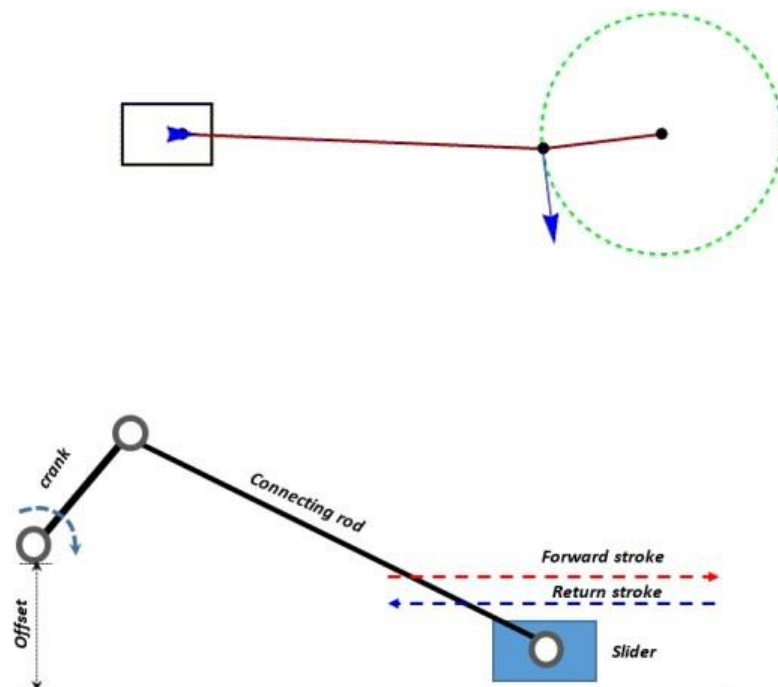
Q34.

Consider the following slider-crank mechanism. As the crank rotates, the slider moves back and forth. Do you think that, if the crank rotates at a constant speed, the slider will take different amounts of time to complete forward and return strokes?

○ Yes.
○ No.

Q36.

For any position of the slider, can you predict the angle θ?

○ Yes.
○ No.

Q37. On a scale from 0-10, with 0 being the lowest and 10 being the highest, indicate how

confident you are in your responses to the engineering design portion of the survey.

0   1   2   3   4   5   6   7   8   9   10

Appendix B: Initial Survey Answer Key

9. a.) Increase. b.) Increase. c.) Decrease. d.) Decrease.

10. An inlet with a large radius and an outlet with a small radius.

11. Answers may vary.

13. Circumferential direction.

14. Answers may vary.

16. Red rope.

18. Two correct answers: red rope and brown rope.

20. Answer marked as correct if participant indicated that the maximal deflection point was slightly to the left of where the force was applied. Answers from 0.55 m to 0.74 m along the beam were accepted.

22. 1 m mark (far right edge of the beam).

24. Answer marked as correct if participant chose a distance in between the two supports.

26. Multiple correct answers: BC, CD, AC, AD, and DE.

27. Answers may vary.

29. Incorrect diagram; question removed.

30. Incorrect diagram; question removed.

34. Yes.

36. Yes.