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INFORMATION OPERATIONS: A MODEL FOR CHARACTERISING THE INFORMATION INTERACTION OF ENGINEERS

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ABSTRACT
As part of the design process information is constantly generated and used by engineers. One approach to improving the design process is to improve the use of information. To do this it is necessary to understand how engineers interact with information. Understanding about how engineers interact with information is fragmented across disciplines. Improved methods of investigating information use, such as eye tracking, address many of the issues of protocol analyses. Using gaze as an indicator of cognitive process, a model of information interaction is proposed, consisting of four information operations; familiarisation, finding, comprehension and review. In this paper a means of testing this model is presented and the construction of the stimuli for an eye tracking study are discussed. A limited prototyping study is used to demonstrate how testing of an information operations model would work with some practical considerations discussed.

Keywords: information operations, eye tracking, cognitive processes

1 INTRODUCTION
Throughout the design process information is generated and utilised by engineers and other users. One approach to improving the design process is to improve the means by which information is utilised. To do this, it is necessary to understand how engineers interact with information. In design research a common means of accomplishing this is to analyse design artefacts. Here, design artefacts are considered as repositories or externalisations of design information and can represent either the process of manufacture, the procedure of design, or the product itself. Examples of design artefacts include sketches, prototypes, specifications and reports.

There are two aspects of engineers' use of information in the design process; the functions supported by design information embodied in design artefacts and the underlying cognitive processes by which engineers interact with design information embodied in design artefacts. How design artefacts are used to support functions, such as communication and collaboration, has been investigated extensively already [1], [2]. However, the cognitive processes that govern the means of interaction with design artefacts, has only been undertaken in part and understanding is fragmented across several disciplines.

Existing attempts to understand the cognitive processes of engineers have relied heavily on protocol analyses, which have limitations when investigating implicit and tacit behaviours [3].

This paper proposes a model of *information operations,* which can be used to characterize how engineers interact with information. To explore this proposition, a series of tightly controlled stimuli information sources have been generated relating to engineering design. The stimuli information sources have been developed for use with eye tracking, a technique widely used as an indicator of cognitive process. The paper describes the development of the information sources and the means by which eye tracking can be used to test the model of information operations. Preliminary testing with a prototyping sample of participants is presented with experimental methodology and hypothesis implications discussed.

1.1 Design information and design artefacts
The complexity of engineering design necessitates the externalisation and recording of design information in the form of design artefacts. Design artefacts can be used to fulfill multiple functions for multiple individuals at different stages of a product's development. For example, the same sketch

can be used to embody an idea and communicate it. This paper takes a different perspective, by considering design artefacts primarily as a repository for design information with an aim of characterising the interaction by engineers with the embodied design information.

The number of functions a design artefact may support is extensive and highly varied, from communication to sense making. Investigating the cognitive processes of the engineer in relation to functions, whilst important, is likely to result in an understanding of cognitive processes specific to that function. A broader approach is to develop a model of information interaction independent of function that can be used to describe the cognitive processes of the engineer whilst interacting with design artefacts. To do so requires a means of categorizing design artefacts that is independent of their function and relates more closely to the notion of design artefacts as externalisations or repositories of design information. Hubka [4] proposes such a means of categorizing the embodied information of design artefacts by considering them as representations with three different forms:

- Symbolic design representations – a representation using assumed or conventional symbols e.g. language, mathematics
- Iconic design representations – a visual record of the original form of the finished product e.g. sketches, drawings, photographs, physical models
- Diagrammatic design representations – a simplified representation of the finished product e.g. graphs, schematics, relationship diagrams.

Typical types of information that are created and utilised as part of the design process include geometry, rationale, performance (test results) and sequences (operation, assembly etc.). This information can be represented in a number of ways. For example, geometry can be represented symbolically with a list of dimensions, or iconically using a scale drawing. The efficacy of means of representation is not within the scope of this paper, nor the difference between how engineers interact with different types of information (geometry vs. rationale for instance). Before either of these issues can be addressed a basic understanding of how representation form affects interaction is required as it is well documented that the cognitive processes associated with using symbolic sources (i.e. reading text) and using iconic sources (i.e. perceiving an image) are distinctly different.

1.2 Designerly intelligence and information operations

Cross [5] argues the existence of a Designer Intelligence, based on the theory of multiple intelligences by the eminent psychologist Gardner. Whilst at the time Cross found insufficient proof to outright satisfy the conditions for a separate Designer Intelligence, as laid out by Gardner, he declared the available evidence to be compelling, strongly suggesting the existence of 'designerly ability'. One of Gardner' key tests for a separate intelligence is the identification of a set of core operations. It is proposed, in support of Cross' claim of a Designer Intelligence, that such a set of core operations exist in relation to the interaction with information embodied by design artefacts. The core operations proposed are a set of information operations, which describe the cognitive actions an individual may perform when interacting with information embodied in a design artifact (Table 1).

Table 1. Information operations model

Information operation	Definition	Details
Familiarisation	The acquisition of information without a specific goal	Strategies for problem solving require an individual to identify an exact or analogous solution from their own long-term memory. Simon [6] discusses the continual process of information acquisition that designers undertake as part of their work and the importance that this plays in ill-defined problem solving. In such situations, information that has previously been gathered for an ill- or underspecified use will be used at a later date in a manner that cannot be predicted.
Finding	The acquisition of information with a specific goal	Providing a specific goal to an individual makes the action of searching fundamentally physiologically different to that of familiarisation. The operation naturally requires additional cognitive effort from the individual and a higher level of engagement as a target must be held in mind and incorrect targets discriminated [7]. Strategies for Finding are therefore likely to manifest differently to those employed during Familiarisation.
Comprehension	The learning of information with understanding	Comprehension occurs when external input information to an individual matches with internal concepts already stored in their memory [8]. Key to comprehension is the notion that the information is stored in a redundant manner, in that it can be reconstructed from the remainder should a portion be forgotten [6]. An individual's degree of comprehension operates on a scale. Dependent on this is whether literal or inferential comprehension has occurred. In literal comprehension all the information is contained within the source, in inferential comprehension the individual must draw upon additional information [8].

Reviewing	The assessment of information to determine quality and validity	In the selection of information sources the perception of quality and legitimacy has been shown to be an important factor [9]. In judging which source to trust the engineer is making an assessment as to the validity of what is presented. The process of review requires an individual to make inferential references to information beyond that which is presented. Comprehension is required for the judgement to be meaningful, though no assumption as to accuracy of assessment is implied.

These information operations are limited to pre-existing information and deliberately exclude the generation or creation of design artefacts. The processes underlying creation is a subject of research in it's own right and does not fall within the scope of this paper.

1.3 Characterising information operations

A series of tightly controlled engineering information sources have been designed for use with eye tracking. The information sources will be used to develop the model of information operations by testing, discriminating and subsequently characterising the visual behaviour associated with each operation. Using Hubka's [4] categorisation of design representations, the information sources have been generated so as to be either symbolic (consisting mostly of text), or a combination of iconic and diagrammatic (consisting mostly of images). By doing so, visual behavior and information interaction can be compared between the two types of representational form.

2 DEVELOPING INFORMATION SOURCES FOR CHARACTERISING INFORMATION OPERATIONS

With substantial literature already on the characterisation of certain perceptive activities, parallels between a model of information operations can be sought and used as a baseline. In this paper the information operations model is limited to considering symbolic representations only. Iconic and diagrammatic representations are a parallel stream of research not within the scope of this paper. Using reading and information seeking respectively as analogous to comprehension and finding, key gaze characteristics such as average fixation durations can be used to develop the information sources for an eye tracking experiment. This section details the design and development of these information sources, with key considerations and concessions discussed.

2.1 Considerations for using eye tracking

A fixation occurs when eye movements are stabilised over an object of interest that is stationary [10]. The duration of fixations required for conscious awareness, or recognition, vary according to the stationary target and the individual. During reading, recognition of words requires a fixation in the order of 200ms [11]. Fixation counts are a measure of the number of fixations, as set by the fixation filter (the experimenter determined threshold of fixation awareness). The movement between fixations is known as a saccade. The distance between the fixations is subsequently known as the saccadic length or amplitude. These gaze metrics, amongst others, will be used to characterise information operations in conjunction with engagement sequence and distribution across the information sources.

In all eye tracking studies it must be noted that the systems track only the foveal region of vision, that responsible for 'high definition viewing'. The region is relatively small accounting for a couple of percent of the entire field of vision. The assumption is made that attention is linked directly to foveal vision, though with conscious effort it is possible to place attention on the peripheral and parafoveal regions [10]. Tasks requiring detailed inspection, such as reading, can be assumed with a high degree of confidence that fixation of a target indicates conscious awareness. That is, text cannot be read without looking within the foveal viscinity of the word. This is in contrast to scene perception whereby the form of a shape may be perceived without the need for foveal vision. As an eye tracker only detects foveal vision, such visual behaviour is not readily detectable.

2.2 Construction of stimuli information sheets

In total, 15 symbolic information sheets have been constructed; three for familiarisation, finding and comprehension and six for review. Review is considered a special case as the agreed understanding of what constitutes the operation is more fragmented within literature from a gaze perspective. Until a point whereby review as an information operation can be elucidated, two elements of review will be tested and compared. These are review critique, and review selection. Review critique requires the assessment of information against a set of criteria; review selection requires the selecting of the most appropriate information from an available range, against a set of criteria. An example of a completed information source is presented in Figure 1.

Single row deep groove ball bearing

Bearing description and capabilities

Deep groove ball bearings are particularly versatile. They are simple in design, non-separable, suitable for high and very high speeds and are robust in operation, requiring little maintenance.
Single row deep groove ball bearings have deep, uninterrupted raceway grooves. These raceway grooves have a close osculation with the balls, enabling the bearings to accommodate radial loads and axial loads in both directions. Single row deep groove ball bearings are available open or capped (with seals or shields). Open bearings that are also available capped, may have recesses in the outer ring.

Bearing requirements

Applied load	Speed	Contamination levels	Operating temperature	Required operating life	Shaft diameter	Bearing max outer diameter
P	*RPM*	η_c	*°c*	*Cycles (millions)*	*mm*	*mm*
1.5 kN	*12,000*	*Low*	*110 °c*	*526*	*30*	*70*

Influence of load and viscosity on reference speed

The main purpose of the reference speed (thermal) is to provide a quick assessment of the speed capabilities of a bearing based on standardized reference values for the heat flow density as established in ISO 15312. When load or viscosity values higher than the reference values are applied ($P = 5\% \, C_0$), the frictional resistance increases and the reference speed should be adjusted. Conversely, lower viscosity or load values can enable higher speeds.

Adjusted reference speed calculation

η_{ar} = Adjusted reference speed (RPM)
η_r = Nominal reference speed (RPM)
f_P = Adjustment factor for bearing load P
f_v = Adjustment factor for oil viscosity

$\eta_{ar} = \eta_r f_P f_v$
$f_P = 0.95$
$f_v = 0.75$
$\eta_r = 28{,}000$
$\eta_{ar} = 19{,}950$ RPM

Modified bearing life

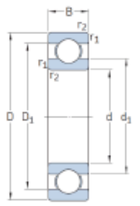
ISO defines the rating life as that exceeded by 90% of a group of apparently identical bearings subjected to an identical load before noticeable evidence of fatigue develops. For modern high quality bearings, the basic rating life can deviate significantly from the actual service life in a given application. Service life in a particular application depends on a variety of influencing factors including lubrication, the degree of contamination, proper installation and other environmental conditions. Therefore, ISO 281 uses a modified life factor to supplement the basic rating life.

Calculated bearing life

Life adjustment factor for 99% reliability $(a_1) = 0.25$
Operating conditions factor $(a_x) = 8$
Applied load $(P) = 1.5$ kN
Dynamic load rating $(C) = 13.8$ kN
Ball bearings $p = 3$
L_{nm} = *adjusted number of cycles (millions)*

$L_{nm} = a_1 a_x (C / P)^p$
$L_{nm} = 0.25 \times 8 \times (13.8 / 1.5)^3$
$L_{nm} = 1548$ million cycles

Single row deep groove ball bearing diagram



Product data (selected bearing in green)

Principal dimensions			Basic load ratings		Fatigue load limit	Speed ratings	
d	D	B	C (dynamic)	Co (static)	Pu	Reference speed	Limiting speed
mm			kN		kN	r/min	
30	42	7	4.49	2.9	0.146	32,000	20,000
	47	9	7.28	4.55	0.212	30,000	19,000
	55	9	11.9	7.35	0.31	28,000	17,000
	55	13	13.8	8.3	0.355	28,000	17,000
	62	16	20.3	11.2	0.475	24,000	15,000
	62	16	23.4	12.9	0.54	24,000	15,000
	72	19	29.6	16	0.67	20000	13000

Figure 1. Example of a symbolic information sheet on the subject of bearing selection

2.2.1 Subject

The SEED Procedural Design Guides have been developed in a consortium of design education professionals from UK universities. The guides outline best practice in design education for the design and selection of several engineering components and feature prominently in the curriculum of mechanical engineering undergraduate degrees in the UK. Examples of subjects covered by the SEED Procedural Guides include gear selection, belt drive selection and rotary power transmissions. By basing the formation of any information source on the SEED Procedural Guides it can be assumed that the subject content is of a suitable level and appropriateness for a variety of graduate level mechanical engineering professionals. It is acknowledged that the generation of information (e.g. performing calculations) is a key aspect of the SEED Procedural Guides, and the cognitive processes of engineers, but at this stage focus is on the interaction with pre-existing information. In this instance, design and selection relies heavily on pre-existing information in the form of instructional guides, such as those found within the SEED Procedural guides and manufacturer catalogues. Therefore, it is important to understand the cognitive processes of interacting with pre-existing information.
Each information sheet will be a representation of a single iteration of a design and selection process for an individual component. For subject content the SEED Procedural Guide on Rolling Element Bearings in conjunction with the official SKF guide to bearing selection have been used.

2.2.2 Content and topics

The content of each information sheets needs to realistically reflect that found within a typical iteration of a bearing selection cycle. Bearings can be selected on the basis of a number of factors from loading, speed, environmental conditions and so on. Fundamental to the process of bearing selection is the need to perform some basic calculations regarding these factors, and then to relate them to the capabilities of different types of bearings. Therefore, each information sheet should contain content including descriptive and qualitative statements about bearing type capabilities, bearing requirements, associated bearing calculations and bearing data such as dimensions. A bearing arrangement diagram is included as to exclude one would unnecessarily complicate an individuals understanding regarding the configuration of the bearing elements to such a degree as to likely interfere with the experiment.

Bearing design and selection is a large subject with several constituent topics. Topics cover the considerations for selecting bearings depending on different factors. Example topics include, selecting bearings on static load rating, adjusting reference speed and determining lubrication options. For the symbolic information sheets the subject, that of bearing selection is kept constant. However, learning biases must be taken into account and without varying the topic these are likely to become significant over the course of displaying 15 information sheets. Content elements, such as number of calculations and bearing data tables, are kept constant, but the topics that they describe are varied.

Maintaining subject and varying topic reduces the effect of learning biases but does not eliminate it. There is inevitably a repetition of certain pieces of text, such as accompanying explanations for calculations. These are referred to as sheet generic information. Conversely, the remaining majority of the sheet is sheet specific, directly relevant to the sheet bearing type. It is presumed preferable to have a known, albeit limited, learning bias effect instead of using an alternative subject to bearing selection that may offer greater topic variety but of a lower engineering relevance. Sheet generic information is purposefully isolated to make accounting for any learning effects easier.

2.2.3 Information quantity

Individuals respond weakly to stimuli where large homogenous areas are present [10]. Consequently it is desirable to avoid such areas within the information sheets so as to elicit a stronger response and improve the probability of detecting characterisable behaviour. This raises the issue of quantity and density of information across the sheet. In symbolic representations a simple means of determining quantity is to use a word count. As reading rates for a variety of populations are available it allows for approximations as to suitable display times of each sheet during an experiment. Determining density of information is not as straight forwards. Attempts have been made to control the distribution of information across the symbolic sheets by controlling word count within cells of information, though the margin of difference can be up to 25%. However, the total quantity of information across all 15 sheets, as measured by word count, is limited to +/- 5%. Assuming a reading rate of 250 words per minute (WPM) [12] for standard reading, and an increased rate for scanning (a likely behaviour during finding) of 500 WPM approximate viewing times for the information sheets can be determined.

2.2.4 Layout and formatting

The content of the information sheets has been formatted and altered in layout so that it is both consistent in style and in a form that can be readily used in an experiment utilising eye tracking. From the example information sheet in Figure 1 it should be noted the sheet is divided into cells. This has been done primarily for experimental reasons and is not representative of the original sources. Each row of cells is independent to all the other rows of cells as no cross-referencing to content is made. Although it has not been done, it is possible to re-order the rows randomly though to do so would seem contrived without probable cause.

The visible cell borders are deliberate in that they communicate an explicit boundary to the contents of information contained within. As homogenous areas are kept to a minimum on each sheet, it is assumed that any engagement within a cell is therefore, deliberate and directly linked to the contents of that cell. For analysis purposes the cell borders define the bounding edges of Area’s of Interest (AOIs) for this reason. Margins of each cell are set to 1cm to minimise the effect of offset errors.

Each sheet is A3 in size with the main body of text in 14pt Arial. References identifying the content source, the SKF bearing selection guide, were removed, as was content unrelated to the topic, such as manufacturer serials numbers. In some limited instances spelling corrections were made to the original text as well as editing to achieve word count control across the sheets.

3 EYE TRACKING PROCEDURE FOR INFORMATION SHEETS

The information operations model and information sheets have been developed as part of on going research into the cognitive processes of engineers’ information interaction behaviour. Testing of the model is to be conducted using undergraduate students in the Formula Student project run by the Institute of Mechanical Engineers (IMECHE UK). The Formula Student team will provide the initial participants for testing, with validation with practicing engineers in industry occurring later. In this paper, prototyping of the proposed study is presented with a limited sample of two participants. Whilst no conclusive data or assertions are presented, qualitative analysis of the proposed method and constructed information sheets is made with a discussion about hypothesised gaze metrics for each information operation.

3.1 General approach to testing information operations model

It is theorised that the similarity between the information operations of familiarisation and finding, and between comprehension and review is greater than that between the two sets of information operations. This difference is designated as first order operations, familiarisation and finding, and second order operations, comprehension and review. It is speculated that first order operations compared to second order operations require less cognitive effort, but at this initial stage this remains an assumption. Building on this assumption is that the operations of comprehension and finding are analogous to reading and information seeking, respectively. These are already well established as distinct information interaction behaviours with associated gaze behaviours. It is expected that results from the comprehension and finding tests will correspond to existing data within the literature. To improve the reliability of data, each information operation test will be conducted three times using a different sheet each time.

3.1.1 First order information operations – familiarisation and finding

Familiarisation is the acquisition of information on a subject area or topic where a specific goal has not, or has yet to be set/developed. During the experiment this behaviour is promoted by informing participants that they will be asked a series of questions following display of an information sheet without specifying the questions prior to viewing. Display time is limited to 30 seconds and gaze is recorded during this period. This is repeated for three information sheets with different questions each time.

Conversely, finding, as defined within the framework of information operations, is the acquisition of information for a specific goal. In this instance, participants are informed of the question prior to the information sheet being displayed for 30 seconds. Again their gaze is recorded during the display of the information sheet. This is repeated for three information sheets with different questions each time.

3.1.2 Second order information operations – comprehension and review (critique and selection)

Comprehension, as defined within the framework of Information Operations, is the learning of information with understanding. Participants are informed that they will be asked a series of short questions requiring detailed understanding prior to viewing an information sheet. Display time is limited to 3 minutes after which they are asked to answer two multiple-choice questions. At this point in time the questions are limited to literal comprehension, in that the answers are explicitly stated in the information sheet that the participants will have viewed. This is repeated for three information sheets with different questions each time and the participant's gaze recorded during the display time.

Review, as defined within the framework of Information Operations, is the assessment of information with a view to determine its quality and validity. As previously discussed, review is further divided into review critique and review selection. For review critique participants are informed that they will be asked to determine the suitability of a selected bearing for a given application, with the assumption that the selection is correct. After viewing the information sheet for 3 minutes participants are asked to rate the suitability according to a given set of requirements. This is repeated for three information sheets with different requirements each time. The participant's gaze is recorded during the display of the information sheets.

For review selection, participants are required to select the most appropriate bearing out of a choice of three for a single application. Participants and displayed all three information sheets for three minutes each, consecutively, before being asked to select the most appropriate bearing for the given set of requirements. The participant's gaze is recorded during the display of the information sheets.

3.2 Characterising each information operation as distinct

The information sheets have been designed to control the content and format to all reasonable and realistic levels. To ensure task compliance the experiment questions have also been developed so as to promote only the concerned information operation for that given sheet Therefore, it is hypothesised that any difference in visual behaviour is as a direct result of the tasks.

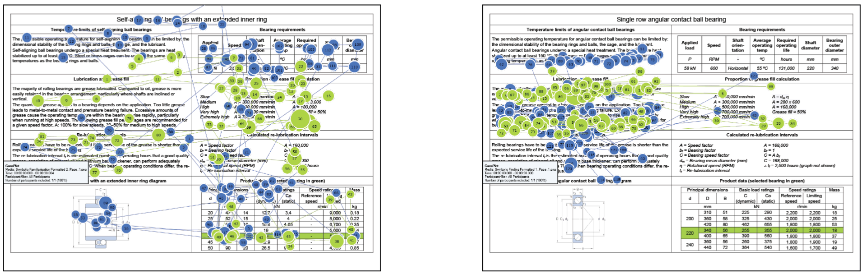
Average saccade length, fixation count, and fixation duration will be determined for each set of three information sheets and tested for statistical difference for each participant. Using the dwell time within any cell as an indicator of engagement, a participant's distribution of engagement will be normalised. The normalised distribution of engagement between the cells of each information sheet, and the cell categories (titles, text, equations, tables, generic information, and specific information) of each information sheet will also be calculated and tested for statistical difference.

4 PROTOTYPING RESULTS

This section presents initial results of two participants during a prototyping stage of the information operations experiment. A Tobii X1 Light Eye Tracker recording at 30 Hz with Tobii Studio 3.2 was used to collect the data on a 1400 by 1080 20" display.

4.1 Familiarisation and finding

In Figure 2 the gaze pattern of the two participants is denoted by the green and blue dots connected by lines. The relative size of the dot indicates the degree of engagement, with closely aligned linear dots suggesting reading. On the finding information sheets, in which the participants are given an information acquisition goal, the engagement is much more closely clustered to the answer location. On the familiarisation sheet the gaze is much more evenly distributed with noticeably longer saccades between fixations. Both participants completed the task on the finding sheets in less than ten seconds. The surplus time was spent re-reading and checking their answers.

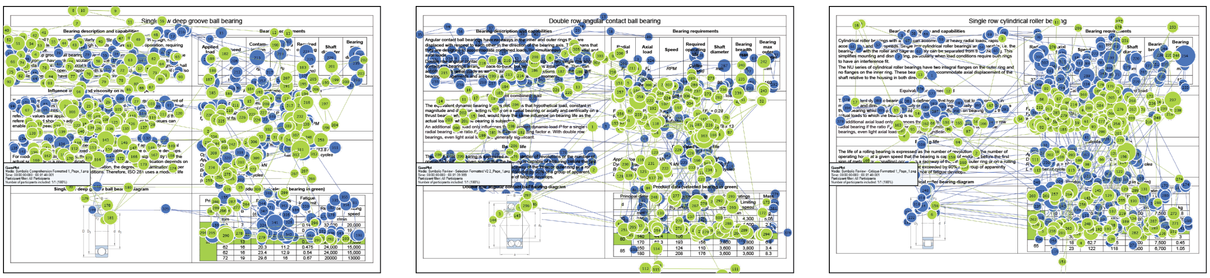


Familiarisation   Finding

Figure 2. Gaze sequence of information operations of familiarization (left) and finding (right).

4.2 Comprehension and review (selection and critique)

In Figure 3 the difference in gaze pattern is not immediately clear compared to the first order information operations. However, it appears that a greater proportion of fixations occur in both review information sheets on specific information to that bearing type (located on the right of the each information sheet). In this area of the information sheet are calculations relating to bearing performance as well as manufacturer data regarding bearing data. The upper most left cell contains a written description of basic bearing capabilities such as the types of loads that can be accommodated.



Comprehension   Review (Critique)   Review (Selection)

Figure 3. Gaze sequence from tasks designed to elicit information operations of comprehension (left) and review critique (top right) and review selection (bottom right).

A restriction of Tobii Studio limits the maximum stimuli display time to 100 seconds. In post testing interviews participants did not feel that they had inadequate time to perform the tasks. For review, participants reported making a decision as to their answer relatively in advance of the maximum allotted viewing time.

5 DISCUSSION

Without a larger number of participants, meaningful data that can be statistically analysed limits discussion and conclusions to qualitative observations. Approximately 50 participants are required to achieve 95% confidence and detect a critical difference of 5% in mean fixation duration for the tasks. Whilst more sophisticated measures than mean fixation duration alone, will be used to supplement the information operations model, it gives an approximate requirement for number of participants.

A potential limitation of any model developed using the procedure described in this paper is the difference in time taken to perform each task and the allocated viewing time. For example, the participants reported completing the finding task in a third of the allowed time, meaning that the remaining 20 seconds was behaviour that would not be associated with finding. The participants, having completed the task to their satisfaction, were free to choose what to engage with. Therefore, comparing the entire 30 seconds of data from finding with 30 seconds of data from familiarisation would result in an error. An alternative is to compare the same 10-second initial segment from both tests. This would however, cause issue with comparing engagement distribution by omitting valid data from the remaining two thirds of the familiarisation task. The same issue is also encountered during the comprehension and review tests, as after having performed the review tasks one or twice, the process of critiquing or selecting was practiced by the participants and inevitably took a shorter period of time.

6 CONCLUSIONS

This paper proposes a model for information interaction by engineers with design artefacts. Four information operations have been identified from literature and are proposed as a means of characterising information interaction. They are; familiarisation, finding, comprehension and review.

The design of an experiment to develop and test this model has resulted in the generation of carefully controlled information sheets to be used as stimuli in a larger eye tracking study. Evidence from literature provides a strong basis for the information operations model, with initial results from a limited prototyping study suggesting the approach to be suitable. Further testing is to occur in the future with a larger sample of undergraduate students and practicing engineers in industry.

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