CIRP Annals - Manufacturing Technology 57 (2008) 149–152

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Use of opposite-relation lexical stimuli in concept generation

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ARTICLE INFO

Keywords:
Conceptual Design
Design Method
Design Stimuli

ABSTRACT

Design description and modeling is widely performed using form-independent functions represented by words in the lexical category of verbs. We have been studying the use of lexical, or word, stimuli in generating design concepts. In this paper, we describe an experiment where participants were provided with problems and stimulus sets consisting of verbs with meanings similar to and opposite to the functional requirements. For all problems, participants were observed to select opposite terms despite their less apparent connection to the problem, even though similar, more obvious terms were present. Results suggest a possible increase in concept novelty when using opposite terms.

1. Introduction

The motivation to study and better understand design and problem solving processes is established by many [1–3]. Investigating how the early phase of design can be better supported is important, as there are fewer formal tools that facilitate the earlier, conceptual stages of design than there are to support later, detailed stages of design. Yet ideas developed during conceptual design have clear implications for the remainder of the design process and the necessary manufacturing processes.

We have been studying as design stimuli the use of language, specifically the meaning, or the semantic component, of words. We are further motivated by research in psycholinguistics and cognitive science showing a connection between language and cognitive functions critical to design such as reasoning [4]. Thus, we study the relationship between language and design in order to exploit this relationship to support the concept generation process in engineering design.

Other applications of language in engineering design include the use of syntax and semantics to evaluate conceptual models [3] and to exchange information for decision-making [5]. Our work in biomimetic/biologically inspired design uses natural-language analysis techniques to retrieve relevant biological analogies as stimuli for design [6,7]. Applications of our approach to biomimetic design include those in microassembly [8], and the design of joints for authorized disassembly [9].

Our language and design work is based on verbs, as verbs represent the part of speech that often best describe design functions. First, problems are decomposed to derive functional keywords. Then, verb taxonomies based on functional keywords are used to generate stimulus verbs denoting actions that are more specific, i.e., hyponyms, or general, i.e., hypernyms. Our previous work, using only similarly related hyponyms/hypernyms as stimuli to determine effects of specificity, indicate that more specific verbs are better than more general verbs as design stimuli [10].

Our current study uses stimulus verbs with meanings that are opposite to the intended functions of the problem. Opposite terms are investigated because they may have advantages of both related stimuli and random stimuli unrelated to the problem to be solved. The use of unrelated stimulus, e.g., a word or picture selected randomly, involves connecting the stimulus to the target problem, where the corresponding thought process has been shown to generate novel ideas. Similar to the use of random, unrelated stimuli, in connecting the contrary meaning of the opposite term to the problem, the designer may be forced to undergo a different thought process that results in different, novel concepts. Yet, opposite terms are still related to the design function, and may be systematically generated through thesauri.

Design methods using opposition include TRIZ [11] and argumentative negotiation [5]. In TRIZ (a Russian acronym for the Theory of Inventive Problem Solving), the problem is phrased in contradictions to identify parameters to be improved and those degraded as a consequence. Argumentative negotiation involves the verbalization of contradictory requirements to produce novel solutions in collaborative engineering.

In this paper, we describe an experiment where participants were provided with problems and associated stimulus sets consisting of similar and opposite terms. Participants were asked to select stimuli for concept generation. We examine the results based on concepts and stimuli selection, and discuss the implications of opposite term stimuli on design novelty.

2. Method

2.1. Participants

Participants were 42 undergraduate engineering students enrolled in a fourth-year mechanical design course.

2.2. Procedure

Participants were given four problems, each with associated stimulus sets consisting of four opposite and four similar terms.

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0007-8506/$ – see front matter © 2008 CIRP.
doi:10.1016/j.cirp.2008.03.023

Participants were allotted 10 min to read each problem statement, perform a functional decomposition, review all stimuli and generate concepts. The problems and stimulus sets were provided on worksheets with space available for participant concepts. Worksheets were collected at the end of the session. Other researchers use similar methodologies to study design [5,12].

2.3. Stimuli

Terms opposite and similar to the functional keywords were generated using lexical resources, i.e., WordNet [13] and a thesaurus [14], and then crosschecked with fluent English speakers to confirm familiarity and to detect pair incompatibility. Table 1 summarizes the problems and shows the associated stimulus sets.

Opposite and similar terms were provided simultaneously and participants were able to select multiple stimuli of either type. We used this hybrid experimental design to mitigate the risks associated with either between-subject or within-subject experiments. Risks with between-subject experiments, where half the subjects receive similar terms only and the other half, opposite terms only, include smaller sample sizes and possibly insufficient data. Risks with within-subject experiments, where the same participants are given one term-type followed by the other for each problem, include possible learning over the course of the two parts of the experiment, and design fixation.

3. Analysis

Each individual concept produced by participants was scored on two metrics, concept completeness and novelty. For each problem, the set of all concepts produced was scored on two other metrics, quantity of concepts and variety of concepts. These metrics are similar to those used by others [12].

Individual concept completeness was evaluated on the degree to which it identifies and fulfills functional requirements using a scale of 0–10. A score of 0 indicates a concept that does not identify functional requirements. A score of 10 indicates that the concept identifies all functional requirements and the methods to fulfill the functional requirements. Only concepts with non-zero completeness scores were further scored using the novelty metric, and included in the concept sets for evaluation using the quantity and variety metrics.

Novelty was evaluated based on the number of individual concepts in each concept category. Concepts in categories with a small number of concepts result in a higher novelty score than concepts in categories with many other similar concepts.

Both completeness and novelty scores are allocated per identified functional requirement and then summed. The problems presented in this study all have two main functions that are equally weighted, i.e., function 1 is as important as function 2. The equation for novelty per concept is given below.

$$N_T = \frac{1}{2}\sum_{i=1}^{2}\sum_{j \in \{a,\ldots,m\}}\left(1 - \frac{n_{ij}}{T_i}\right) \times 10 \quad (1)$$

where N_T = total novelty for an individual concept, T_i = number of concepts for function i, n_{ij} = number of observed concepts in concept category j of function i, with j being one of the concept descriptors {a,. . .,m}. The 1/2 indicates each function is equal. Multiplying by 10 sets the range of novelty scores.

For metrics measuring concept sets, quantity is the total number of functionally complete concepts generated by all participants for that problem, and variety is the total number of observed concept categories for each of the two problem functions.

4. Results

Overall, participants selected similar terms more often than opposite terms (171 similar terms and 107 opposite terms). An independent T-test was used to compare mean concept novelty between two categories:

1. Concepts using at least one opposite term.
2. Concepts using only similar terms.

The mean novelty between the categories was not significantly different for three of the problems (Grinding, Egg-orientation, and Bushing-and-pin). However, for the Sunflower-seed problem, the mean novelty was found to be significantly greater for concepts generated using at least one opposite term ($N = 11$) when compared to the concepts generated using only similar terms: ($N = 9$), $t(18) = 1.98$, $p = 0.032 < 0.05$.

For two problems (Grinding, Bushing and pin), novelty was greater for concepts developed using at least one opposite term, but not significantly greater. The results of the T-tests are summarized in Table 2.

Next, quantity and variety metrics were calculated for the set of all concepts generated per problem. The quantity of completed concepts generally increased with opposite term use. Fig. 1 shows this trend when comparing results for the Grinding and Egg-orientation to the Sunflower-seed and Bushing-and-pin problems.

Concept variety also generally increased with opposite term use. Comparing the results for the Grinding and Egg-orientation problems with the Sunflower-seed problem in Fig. 2 suggests this trend. Fig. 2 relates concept variety for each function with the percent opposite term use for each problem from Fig. 1.

Table 1
Summary of problems and stimulus sets

Problem Description and Decomposition	Stimulus Terms: Similar	Stimulus Terms: Opposite
1. Sunflower-seed shelling for oil extraction—extract seed from encasing shell; separate seeds from shell fragments [15].	Empty Withdraw Disconnect Divide	Fill Insert Join Combine
2. Grinding soft materials—remove/shape surface material; remove/clean chips from tool [16].	Smooth Subtract Clean Remove	Roughen Add Clog Replace
3. Egg-orientation for packing—determine which eggs require turning; turn eggs [16].	Select Detect Pivot Move	Reject Miss Fix, restrain
4. Bushing-and-pin assembly—align bushing and pin; insert pin into bushing [16].	Straighten Match Inject Install	Skew Mix Eject Extract

Table 2
Summary of *T*-test results for concept novelty

Problem	Opp. *N*, Mean	Sim. *N*, Mean	*t*	*p*
Sunflower-seed	11, 6.66	9, 6.03	1.98	0.032
Grinding	29, 7.39	14, 7.19	1.14	0.13
Egg-orientation	23, 7.48	8, 7.86	−1.21	0.11
Bushing-and-pin	11, 7.51	13, 7.27	0.66	0.26

5. Discussion

While percent opposite term use was higher and led to increased concept quantity and variety for the Grinding and Egg-orientation problems as shown in Figs. 1 and 2, concept *novelty* due to opposite term use was only significantly higher for the Sunflower-seed problem, as shown in Table 2. Although the Sunflower-seed problem was presented first in the sequence of problems, a likely stronger factor that led to a statistically significant difference in novelty to be observed in only the Sunflower-seed problem is a relational difference in the stimulus pairs, which is discussed in detail below.

Some pairs may not appear to be direct opposites in the problem context. For example, the direct opposite for "disconnect" would be "connect". However, to avoid obvious opposites denoted by morphological markedness, e.g., "tie/untie", the term "join" was used as an opposite for "disconnect". For the verb "pivot", the direct opposite would be "not pivot", but the terms "fix" and "restrain", both opposite terms of "move", were used. Indirect opposite terms may be selected less as stimuli because their relationship to the problem is not as clear. Furthermore, some stimulus terms are more descriptive than active, where their use in the given form is as much if not more often as adjective than verb, e.g., "smooth" and "clear", and another pair formed a common English idiom, "mix and match" meaning "to select."

The remaining opposite pairs can be divided into contradictory or converse pairs [17]. A contradictory pair imparts mutual exclusivity, such as "live/die", "succeed/fail", i.e., someone cannot succeed and fail at the same time. A converse pair encompasses the same activity but from different perspectives, e.g., "give/take" or "buy/sell". For example, a buyer buys an object that a seller sells. Converse pairs also include a presupposition, e.g., for an object to be bought, it must have been sold. Table 3 summarizes the different stimulus pairs.

Contradictory and converse terms are defined in the context of the original problem situation and objects/nouns. For example, the functional requirements of the Sunflower-seed problem include removing the object "seeds" from the object "shells". Relating the stimulus terms "empty" and "fill" to the problem situation, to empty the shells (of the seeds) is consistent with the intended solution, but it is contradictory to fill the shells (with the seeds). Because of this contradiction, new objects must be introduced so the contradictory term can be used consistently with the functional requirements.

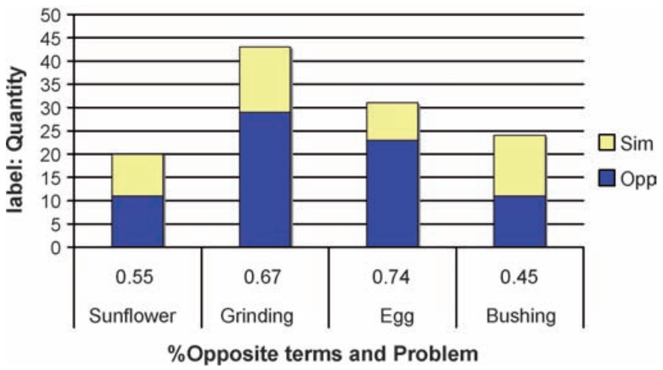

Fig. 1. Concept quantity vs. opposite term use.

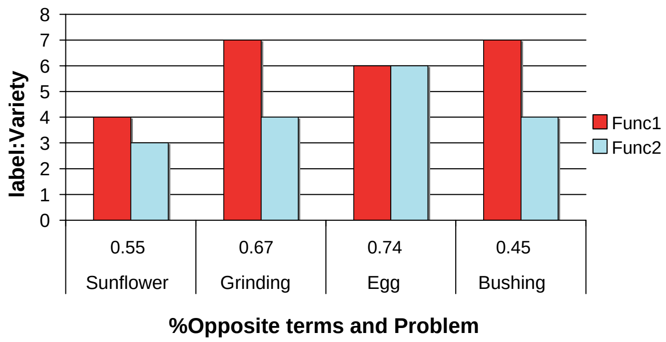

Fig. 2. Concept variety vs. opposite term use.

When participants selected and used the term "empty", it was applied to the original problem objects (e.g., shells and seeds) three out of five times, and introduced a new object (a column to hold shells and seeds) only once. One selection of the word "empty" had an unspecified use. However, for the contradictory opposite term, "fill" was applied only once to an original problem object, and introduced new objects (tank, hopper, basin and water) four times out of six. One selection of the word "fill" had an unspecified use.

For the Grinding problem that involves material removal (or subtraction), the process of "adding" material to the wheel or workpiece would be contradictory. To overcome this contradiction, one subject proposed a larger wheel size by adding "radius" to the grinding wheel. This would reduce the contact time between the workpiece and each point on the wheel, and thus allow more tool cleaning to occur simultaneously during each wheel rotation.

However, when opposite terms are converse terms, concepts developed from either the similar or opposite term are equivalent as both are consistent with the functional requirements. In the Egg-orientation problem, the "select/reject" pair produces the equivalent actions of "select correctly oriented eggs" and "reject incorrectly oriented eggs". "Moving/pivoting an incorrectly oriented egg" is also complementary to "fixing/restraining a correctly oriented egg". In the Bushing-and-pin problem, equivalent actions are described by "inject pin into the bushing" and "eject pin (from a fixture) into the bushing."

Verbs involve the inclusion of different nouns that perform different semantic filler roles [18]. Common semantic filler roles include patients (often direct objects), agents (often subjects), instruments and locations. Contradictory opposite terms appear to introduce new objects/nouns into these roles so that the contradictory term is consistent with the functional requirements of the

Table 3
Term usage and pair types

Similar (#)/Opposite (#)	Pair Type
Sunflower-seed	
Empty (5)/fill (6)	Contradictory
Withdraw (6)/insert (2)	Contradictory
Disconnect (10)/join (1)	Contradictory, indirect
Divide (16)/combine (7)	Contradictory
Grinding	
Smooth (27)/roughen (4)	Contradictory, desc.
Subtract (7)/add (18)	Contradictory
Clear (11)/clog (12)	Descriptive
Remove (16)/replace (7)	Contradictory
Egg-orientation	
Select (6)/reject (16)	Converse
Detect (8)/miss (1)	Converse, indirect
Pivot (17)	Converse, indirect
Move (9)/fix (7)/restrain (9)	Converse, indirect
Bushing-and-pin	
Straighten (7)/skew (3)	Contradictory, desc.
Match (12)/mix (5)	Contradictory, idiom
Inject (8)/eject (4)	Converse
Install (8)/extract (3)	Contradictory

Participant selection frequency indicated in parentheses.

Table 4
Ratio of usage where new objects are introduced by contradictory (w/o desc. and idiom) terms and converse terms

Contradictory, New	Converse, New
(Empty)/fill, 0.667	(Select)/reject, 0
(Withdraw)/insert, 0.5	(Detect)/miss, 0
(Disconnect)/join, 1	(Pivot)/fix, 0
(Divide)/combine, 0.714	(Move)/restrain, 0.111
(Subtract)/add, 0.5	(Inject)/eject, 0
(Remove)/replace, 0	Mean = 0.02
(Install)/extract, 0.667	
Mean = 0.58	

Parentheses indicate similar term.

problem. As mentioned for the Sunflower-seed problem, "fill" introduces a new object to be filled (tank), because filling the shell (an original problem object) would be inconsistent with the functional requirements.

Table 3 shows that the stimuli for the Sunflower-seed problem included three direct contradictory pairs, while the other problems included fewer contradictory pairs or more problematic pairs such as descriptive terms as stimuli. The greater number of contradictory pairs in the Sunflower-seed problem may explain the significantly greater mean novelty in concepts developed for this problem. Table 4 compares the ratio of term usage where new objects are introduced. An independent *T*-test comparing the mean rate of new-object introduction by contradictory terms ($N = 7$), excluding descriptive and idiomatic terms, and the mean rate of new-object introduction by converse terms ($N = 5$) shows that contradictory terms introduce a significantly higher rate of new objects, $t(10) = 3.98$, $p = 0.001 < 0.05$.

Another factor in stimuli selection and use is the type of action denoted by the stimuli. Some actions are physical in nature while other actions are abstract or cognitive. For example, actions denoted by the pairs "select/reject" and "detect/miss" in the Egg-orientation problem are more abstract than physical. Abstract stimuli may be less useful for design problems that involve manipulation or representation of physical objects. Previous work found that abstract words are not as useful for retrieving relevant biological analogies for design [7,19].

6. Future work and concluding remarks

This study suggests that opposite-term stimuli may result in more novel concepts. However, some of the opposite terms provided as stimuli may not have been ideal, e.g., indirect opposites and converse pairs. We believe that contradictory opposite terms result in more novel ideas because contradictory terms force a shift among the selected term's semantic filler roles, introducing new and different objects that correspond to novel concepts. Although converse opposite terms also require a shift in perspective, e.g., correctly vs. incorrectly oriented egg, use of either the similar or opposite term in a converse pair can result in equivalent concepts. The Sunflower-seed problem, with more contradictory opposite terms as stimuli, showed a statistically significant greater mean novelty for concepts developed with opposite terms. Two other problems showed a slightly greater mean novelty for concepts developed with opposite terms.

While this study used a hybrid experimental design, future work includes investigation of opposite-term stimuli using a fully between-subjects experiment to remove the potential confounding effects of simultaneous exposure to similar terms, or a within-subjects experiment to control for differences in individual designers. Problem presentation order will also be randomized to control for any learning effects.

Another challenge warranting further study is systematically distinguishing contradictory opposite terms from converse opposite terms. Thesauri do not distinguish between contradictory and converse opposite terms, and pair type is also dependent on the problem context. We hypothesize that mean novelty will be greater for opposite term use in all problems when the experiment is performed using either a between-subjects design or a within-subjects design, and when only contradictory opposite terms are presented as stimuli.

Further understanding of language as design stimuli enables development of early stage design support tools to exploit connections between language and reasoning.

Acknowledgements

We are grateful for the contribution of the study participants and the financial support of the Natural Sciences and Engineering Research Council of Canada.

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