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UNDERSTANDING THE USE OF LANGUAGE STIMULI IN CONCEPT GENERATION

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ABSTRACT

Natural language, which is closely linked to thought and reasoning, has been recognized as important to the design process. However, there is little work specifically on understanding the use of language as design stimuli. This paper presents the results of an experiment where verbal protocols were used to elicit information on how designers used semantic stimuli presented as words related to the problem during concept generation. We examined stimulus use at the word level with respect to part-of-speech classes, e.g., verbs, nouns and noun modifiers, and also how stimuli syntactically relate to other words and phrases that represent ideas produced by the participant.

While all stimuli were provided in verb form, we found that participants often used stimuli in noun form, but that more new ideas were introduced while using stimuli as verbs and noun modifiers. Frequent use of stimuli in noun form appears to confirm that people tend to think in terms of objects. However, noun use of stimuli introduced fewer new ideas and therefore contributed less to concept formation in our study. This work highlights a possible gap between how people may tend to think, e.g., in terms of nouns, and how new ideas may be more frequently introduced e.g., through verbs and noun modifiers. Addressing this gap may enable development of a language-based concept generation support system to encourage innovative and creative solutions for engineering problems.

Keywords: Conceptual design, design stimuli, language, verbal protocols.

1 INTRODUCTION

Many researchers recognize that natural language plays important roles in conceptual design. Natural language can be used in requirement specification (Burg, 1997; Nuseibeh & Easterbrook, 2000), concept generation (Segers, 2004; Chiu & Shu, 2007a,b), design representation (Pahl & Beitz, 1996; Stone & Wood, 2000), design retrieval and reuse (Stone & Wood, 2000; Yang et al., 2005) and outcome analysis (Mabogunje & Leifer, 1997; Dong et al., 2003).

While natural language is not usually considered an engineering or design tool per se, language innateness in humans makes it difficult to avoid language in the study of the human designer. Language is highly structured and closely related to reasoning (Levinson, 1996; Li & Gleitman, 2002), which suggests that it may be possible to use language itself as a design tool. Within design, the relationship between language and thought in spatial reasoning and decision-making has been acknowledged (Gero et al., 1994; Dentsoras, 2005).

Conceptual design, being an early stage of the design process, is characterized by its lack of complete information and informal nature. Many of the outcomes rest on the designer's intuition and prior design experience (Li & Jin, 2006). Many conceptual design methods encourage designers to go with their "gut feelings" to expand the solution space, but do not attempt to tap into and guide the designer's thought processes.

Language may provide ideal stimuli for conceptual design. While language and words impose a structured and predetermined symbol system on the user (Bruner, 1964), the interpretation of words is still ambiguous and words are not always fixed to a particular form, which is ideal for conceptual design (Segers, 2004). Language, with an established relationship to reasoning, affords a highly structured framework. Yet, the non-fixedness it also affords may facilitate the concept generation process without sacrificing the variety and creativity desired at this stage of design.

In this paper, we examine how designers use semantic stimuli presented as words related to the problem during concept generation. We do so through verbal protocols and content analyses at both word and syntactical levels.

2 RELATED WORK

2.1 Language and design

Verbs, the part-of-speech that conveys actions, are used to model design functions (Pahl & Beitz, 1996; Stone & Wood, 2000). Stone and Wood's functional basis includes a defined taxonomy of verbs that can be used to represent functions. The use of a standardized taxonomy is useful for the storage and retrieval of design within a design repository.

Providing design information in natural language format is useful in design retrieval applications because text-based representation increases the amount of information available for searching (Linsey et al., 2006). Other sources of language-based design information include design notebooks and design documentation (Yen et al., 1999; Dong et al., 2003). However, challenges to studying unstructured natural language include imprecise, incomplete and informal language use. Solutions include building design thesauri (Yang et al., 2005) and design ontologies (Witherell et al., 2006).

In our previous work on identifying relevant biological analogies for design (Hacco & Shu, 2002; Chiu & Shu, 2007a), we used functional keywords expressed as verbs, e.g., "clean" or "remove" to retrieve from knowledge in natural-language text, biological phenomena that involve cleaning and removing. Nouns were less effective as keywords because they tend to be form-specific, typically require previous knowledge and indicate a bias towards a predetermined model. For example, searching for "kidney" requires prior knowledge that kidneys clean, and limits the retrieved phenomena to those related to kidneys, not revealing other less obvious biological systems that also clean and may serve as better analogies.

Using computer aided architectural design (CAAD) systems, word annotations from architects' sketches were collected and examined for use as design stimuli (De Vries et. al, 2005). Words contained in the annotations were used to identify related words. These related words were then presented as feedback to the architect to reduce fixation and promote generation of new concepts. Since both nouns and verbs could be used in annotations and collected, both nouns and verbs could have been used as design feedback.

Although not specifically a language-based design method, De Bono (1992) suggests that designers relate randomly selected stimuli to their problem to gain new perspectives. The random stimulus could be in the form of a picture from a catalogue or a word from a dictionary. Pictures of objects likely would be mentally represented as nouns.

In our most recent work on using language as related stimuli (Chiu & Shu, 2007b), participants recorded their solutions to design problems on worksheets. In these "pen-and-paper" experiments, a set of verbs functionally related to the problem was provided as stimuli. This study showed a good correspondence between words chosen as stimuli and completed concepts. Also found was that verbs with two specific properties were used more successfully to generate complete concepts.

The first property is the specificity of a verb, e.g., sauntering is more specific than walking, as it is a particular manner of walking. More specific verbs were more successfully used than very general verbs, e.g., moving, but verbs that were too specific may be difficult to relate to the problem. Less specific words tended to be more successful when they were used in conjunction with more specific words. The use of less specific words to develop concepts may be indicative of the ability to perform higher-level abstraction. Dong (2006) found that the expression of hypernym relationships in design conversations suggests the capacity for higher-level abstraction, often required of successful designers.

The second property has to do with the verb's degree of transitivity, i.e., the number of different senses or meanings of the verb that can take direct objects. More transitive verbs, i.e., those with more senses that can take direct objects, were more successfully used than less transitive verbs. This result may be because engineering problems tend to be transitive in nature, and therefore transitive verb stimuli were more useful.

However, as only the final response was recorded in pen-and-paper experiments, it was often difficult to infer participants' use of word stimuli during the course of the process. The current experiment collected continuous data through a reporting technique known as verbal protocols.

2.2 Verbal protocols as data in engineering, design and problem solving studies

In verbal protocols, participants are asked to "think aloud" as they work on a task. Some believe that the verbalization process itself affects the thought process, and thus the task. Ericsson & Simon (1993) however, argue that since verbal on-line reporting draws on short-term memory, i.e., facts and thoughts already present, such verbalization would not alter the thought process. Despite the debate on the validity of think-aloud reporting, verbal protocols have been used to gather data in many problem-solving and engineering design studies. These include the study of problem solving in thermodynamics (Bhaskar & Simon, 1977), differences in problem solving between creative and noncreative students (Goor & Sommerfeld, 1975) and trouble-shooting techniques of skilled electronic technicians (Rasmussen & Jensen, 1974).

More recent use of verbal protocols in engineering includes studies on the differences between freshmen and senior engineering designers (Atman et al., 1997) and stimulation of creativity in conceptual design (Benami & Jin, 2002).

3 NOMENCLATURE

Adjective – Word that modifies a noun, e.g., black in "*black* box" and matching in "the *matching* contour." Also see noun modifier.

Constituent – Phrase within a sentence or a larger phrase, e.g., noun phrase, verb phrase or prepositional phrase. For example, the prepositional phrase "to the bushing" is a constituent of the verb phrase "attach the guide to the bushing."

Function words – Words belonging to grammatical or function classes such as articles, conjunctions and prepositions (Akmajian et al., 1998), e.g., *this* and *a* in "*this* guide is more like *a* fixture".

Hypernym – Describes the superset of a word, where the hypernym encompasses all instances of x. For example, *tree* is the hypernym of maple (Miller, et al., 1993).

Hyponym – Describes a subset of a word, where the hyponym is a specific instance of y. For example, *tree* is a hyponym of plant (Miller, et al., 1993).

Noun – Word that denotes an object, thing or concept.

Noun modifier – Noun that is used to modify a subsequent noun, e.g., wool in "*wool* sweater" vs. "woolen sweater" and skew in "the *skew* problem".

Noun phrase – Phrase based on a noun, e.g., "the long *street*" and "a paper *wad".*

Object – Receiver of verb, e.g., ball in "Pat threw the *ball*", and alignment in "you modify the *alignment*".

Oblique object – Indirect object or object of prepositional phrase (Trask, 1999), e.g., me in "He threw *me* the ball" or "She threw the ball to *me*", and storage in "get the coal from *storage".*

Parts-of-Speech (POS) class - Also known as word classes, e.g., nouns, verbs, adjectives, etc.

Prepositional phrase – Phrase that starts with a preposition, e.g., "around the house" is a prepositional phrase contained in "you can force snow *around the house*".

Subject – Someone or something of which something is said or described, e.g., metal in "*metal* displaces water". Often includes the role of an agent (Matthews, 1997), e.g., Pat in "*Pat* threw the ball".

Semantics – Study of linguistic meaning and interpretation at different levels, e.g., word, phrase, sentence, text, etc. (Chierchia & McConnell-Ginet, 1990).

Syntax – Study of relations between words and other units in a sentence (Akmajian et al., 1998).

Troponym – Hyponym relationship between verbs specifically (Fellbaum, 1993), e.g., "to amble" is a troponym of "to walk" because *ambling* is a particular manner of walking.

Verb – Word denoting an action, a process or a state.

Verb phrase – Phrase based on a verb, e.g., "*force* the snow into a blanket".

4 EXPERIMENTAL METHOD

4.1 Participants

Participants consisted of three male, fourth-year Mechanical and Industrial Engineering students at the University of Toronto. At the time of the experiment, all were enrolled in a fourth-year engineering design course. All participants are fluent English speakers. Although English was not the participants' first language, they all reported having learnt English at a young age and that they currently "think" in English. The participants were paid for their participation in this experiment.

4.2 Procedure

Participants were instructed to "think-aloud" and verbalize all thoughts and reasoning as they worked through three design problems. They were first given a series of practice arithmetic and word problems to habituate or train them in the process of verbalizing while working on a task. For example, in the arithmetic problem, participants who only provided the final answer were instructed to repeat the problem while verbalizing each step required to produce the final answer. The practice problems were presented on worksheets that allowed for written annotations, e.g., calculations, sketches, etc.

Each experiment problem, also presented on a worksheet, included the problem statement and a set of stimulus words generated using keywords from the problem statement. Also included were instructions to perform a functional decomposition of the problem, and to review all stimulus words before developing concepts. The stimulus set was generated using the WordNet hierarchy (WordNet, 2.0). Words were displayed randomly, and not within a hierarchy, on the worksheets.

Participants were given a total of 15 minutes per problem. If they were silent for any length of time, they were prompted to keep talking. The sessions were recorded and transcribed.

The transcriptions were separated into clauses each containing one main verb. We then determined the parts-of-speech (POS) classes in which stimulus words were used. Although stimuli were intended as verbs, participants verbalized the stimulus words in other POS classes. We also studied the relationships between stimuli and other words through an explicit content analysis. Specifically, we used a keyword-in-context (KWIC) (Weber, 1990) search to examine stimulus usage and relationships to other words expressed by the participants.

4.3 Problems

The problems used in the experiment are given below. The first problem involves manufacture/assembly, which we felt the participants, mechanical engineering students, could handle.

The last two problems are general and do not require specific knowledge.

Experiment problem 1:
Parts that are automatically mated, e.g., a bushing and a pin, must be positioned so that their axes coincide. Using chamfers on mating parts does not solve the alignment problem. Develop a concept to center mating parts that does not require high positioning accuracy (Kosse, 2004).

The stimuli were presented as shown below to the participants. The original keywords used to generate the below are "align" and "insert".

Inject		Mount		Adjust
Transplant	Connect	Misalign	Join	
			Reorient	Modify
Sandwich		Attach		Match
	Skew			

Experiment problem 2:
In Canada, snow is readily available in the winters and has good insulating qualities due to the amount of air in it. However, if the snow is packed to the point it becomes ice, it is less insulating due to the loss of air. Come up with a concept to enable snow to be used as an additional layer of insulation for houses in the winter.

The original keywords "pack" or "compact" led to stimulus words: push, impact, compress, squeeze, contract, arrange, bundle, force, change, move, wad, tighten, constrict. The stimulus set was presented randomly in a grid as for the previous problem, but simply listed here for brevity.

Experiment problem 3:
Clean coal and clean coal combustion technologies make it possible to generate cleaner electricity. That, combined with the increasing cost of oil and natural gas, power plant operators may consider converting or reconverting their power plants from oil or natural gas back to coal. However, there may not be enough land area near the plant that can be used for on-the-ground coal storage. Propose alternative solutions to a conventional coal pile (adapted from Dieter, 2000).

The original keyword "store" led to stimulus words: collect, accumulate, bottle, place, withhold, supply, give, heap, displace, feed, keep, distribute, transfer.

4.4 Word stimulus sets

WordNet was used as a language framework to generate the related stimulus sets. WordNet is an online lexical database that is organized according to psycholinguistic theories of human lexical memory, where words are stored in hierarchies according to their semantic relatedness to other words (Miller et al., 1993). This is unlike a dictionary where words are organized alphabetically regardless of semantic relationships to adjacent entries.

All stimulus sets were generated from WordNet verb hierarchies and consist of verbs residing in levels 1 through 4 of the hierarchy. Verbs that are specific instances of actions are known as troponyms, while verbs that describe the superset of actions are known as hypernyms. For example, "to amble" is a troponym of "to walk", and "to move" is a hypernym of "to walk." Level-1 words are hypernyms of level-2 words, which are hypernyms of level-3 words, and so on. Figure 1 shows an example of a partial stimulus hierarchy for the bushing problem.

The "#number" following each word indicates the WordNet sense, or meaning, of the word applicable to the hierarchy generated. Words have multiple senses, and WorldNet enumerates these senses based on the commonness of the sense.

The number following the sense is the weighted intransitivity of each word. Transitivity refers to whether a verb can take a direct object. Some senses of the same word may be transitive while others are intransitive. The weighted intransitivity gives more importance to the more common senses of the word that are intransitive (Chiu & Shu, 2007b).

Each stimulus set contained 13 verbs with different levels of specificity and degrees of intransitivity. Every effort was made to include words from all specificity levels, words that were transitive as well as moderately and wholly intransitive, and words that ranged between familiarity and obscurity. However, the stimulus sets were restricted by the available words with desired properties within WordNet. These properties are known to be relevant from previous work (Dong, 2006; Chiu & Shu, 2007b). However, since we focus on how participants used the stimuli and not the stimuli themselves, these properties are not as important in this study as they were in previous studies. All stimulus words were presented in root verb form. No definitions of words were given, nor was the use of words illustrated in sentences.

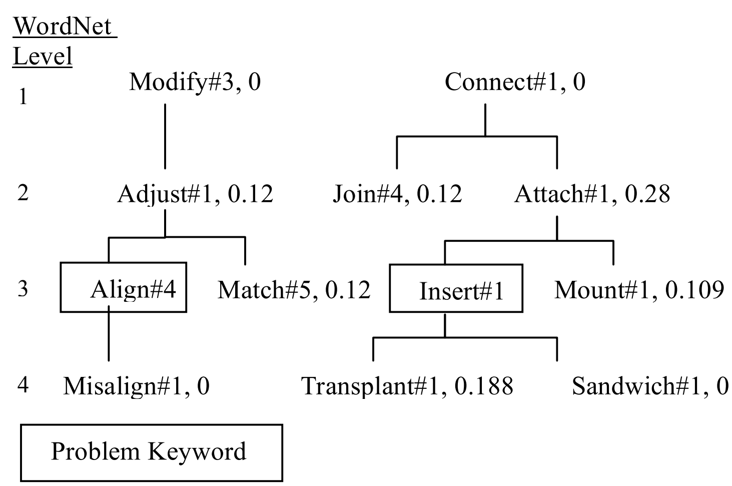

Figure 1: Partial stimulus hierarchy for the bushing problem.

5 OBSERVATIONS AND RESULTS

We first present observations and results of participant behavior, including participant concepts. Next, we examine the content of the verbal protocols to categorize how participants used stimulus words e.g., as verbs, nouns or noun modifiers. Finally we relate the stimulus used by the participant to other words and phrases produced by the participant.

5.1 Participant behavior

Participants 1 and 2 were able to verbalize continuously throughout the experiment. These participants produced approximately the same number of content-bearing words (words that carry meaning) and unique words (the same word repeated was counted only once). Participant 1 commented that he often talked to himself while solving problems on his own.

Participant 3 did not verbalize continuously and required prompting to continue talking throughout the experiment. Participant 3 produced half the number of content-bearing words as Participants 1 and 2. This participant relied on writing as his main method of working through the problems. However, he was able to explicitly relate his concepts to the associated stimulus words, enabling a direct mapping between stimulus words used and concepts.

Since participants were instructed to review all stimuli first, most words were used at least once by at least one participant, and not only in a listing or isolated utterance.

5.1.1 Concepts

Specific stimulus words were associated with the concepts developed by participants. These associated words were identified through explicit indication and syntactical analysis.

Table 1 summarizes participants' final concepts and the stimulus words associated with the concepts. Tables 2-4 show for the words associated with concepts, the word level, intransitivity, participant use and frequency of use for each problem. While some stimuli were used frequently, e.g., the word "match", frequent use of stimuli does not always contribute strongly to the associated concept. No clear patterns emerged in the type of concepts produced. Our previous pen-and-paper experiment that involved more participants resulted in more distinct concept classes.

Table 1: Participant concepts and associated stimulus words.

	Participant 1	Participant 2	Participant 3
Bushing	Solution: Use a semi-circular channel to guide the pin into the bushing. Associated stimuli: Attach, match	Solution: Use a signal to indicate axes match while using trial and error. Associated stimuli: Attach, join, match	Solution: Create an injection gun. Associated stimuli: Inject
Snow	Solution: Use a funnel to direct snow down the side of the house walls and pump to re-circulate the snow to prevent compaction. Associated stimuli: Constrict, move, force	Solution: Make snow bricks and stack them next to the house. Associated stimuli: Constrict, compress, change	Solution: Create a snow blanket that can be applied over windows at night. Associated stimuli: Force, bundle, constrict, squeeze
Coal	Solution: Distribute the coal storage over a wider area and then transfer it to plant via conveyors. Withhold supply until needed. Coal can be stored in high heaps. Associated stimuli: Distribute, transfer, heap, withhold	Solution: Build tall storage towers. Associated stimuli: Supply, keep	Solution: Store small amounts near the plant and have a larger supply further away. Associated stimuli: Bottle, supply, heap

Table 2: Bushing problem: Associated words, word level, intransitivity and participant use.

Stimulus associated with concept	Level	Ratio of intransitive to total senses, %Weighted intransitivity	Participant# (frequency)	Total frequency
Attach	2	2/5, 0.28	1(2), 2(2)	4
Inject	4	0/6, 0	3(2)	2
Join	2	2/5, 0.12	2(3)	3
Match	3	2/10, 0.12	1(19), 2(6)	25

Table 3: Snow problem: Associated words, word level, intransitivity and participant use.

Stimulus associated with concept	Level	Ratio of intransitive to total senses, %Weighted intransitivity	Participant# (frequency)	Total frequency
Bundle	4	0/7, 0	3(3)	3
Change	1	4/10, 0.21	2(4)	4
Compress	3	0, 0	2(2)	2
Constrict	3	0, 0	1(3), 2(4), 3(2)	9
Force	2	0, 0	1(1), 3(3)	4
Move	1	11/16, 0.375	1(5)	5
Squeeze	2	0, 0	3(1)	1

Table 4: Coal problem: Associated words, word level, intransitivity and participant use.

Stimulus associated with concept	Level	Ratio of intransitive to total senses, %Weighted intransitivity	Participant# (frequency)	Total frequency
Bottle	4	0, 0	3(6)	6
Distribute	3	2/11, 0.058	1(18)	18
Heap	3	0, 0	1(9), 3(5)	14
Keep	2	3/22, 0.105	2(11)	11
Supply	3	0, 0	2(4), 3(7)	11
Transfer	1	1/9, 0.111	1(15)	15
Withhold	4	0, 0	1(6)	6

5.2 Stimulus parts-of-speech classes

We examined stimulus parts-of-speech (POS) use through the compilation of the keyword-in-context (KWIC) lists (Weber, 1990). A transcript sample of Participant 1 working on the bushing problem and the corresponding analysis follows. As previously described, the transcriptions were separated into clauses each containing one main verb, which are enumerated below. Italics denote stimulus words used by the participant.

1: *Misalignment* is definitely a problem
2: So if we just *match* one
3: If we just *match* one
4: Then what I'm trying to achieve is to *match* others at the same time
…
16: *Misalign*
17: *Misalign* is what we're trying to solve here
18: And *skew* is definitely one of the problems
19: So if we solve the *skew*

The KWIC list for the stimulus "misalign" follows:

1: MISALIGNment is definitely a problem
16: MISALIGN
17: MISALGIN is what we're trying to solve here

Similarly, the KWIC list for the stimulus "match" follows:

2: So if we just MATCH one
3: If we just MATCH one
4: Then what I'm trying to achieve is to MATCH others…

This analysis facilitates determination of the POS and context of usage. For example, in clause 1, "misalign" was used in a noun form. In clauses 2-4, "match" was used as a transitive verb. In clause 16, it was not possible to determine the intended POS form of "misalign".

While stimuli were presented in root verb form, participants frequently used stimuli in both verb and noun form. Occasionally, participants also used stimuli as adjectives or noun modifiers.

Words that were designated as adjectives or noun modifiers could either be in the adjectival form, e.g., "*misaligned* pin", or the noun form used to further describe a subsequent noun in a noun phrase, e.g., "*injection* gun". Although adjectives and noun modifiers are not identical, we counted them in the same category because they both: describe objects, did not represent described objects themselves, and did not describe actions. We did not find any instances of stimulus words used as adverbs.

Words were designated as "unknown" when it was impossible to determine the participants' intended POS, e.g., when the participant listed the words singly, or uttered them in isolation. Undetermined usage did not contribute to the overall frequency totals and other calculations.

Bar graphs summarizing stimuli used as verbs, nouns or noun modifiers are shown in Figures 2-4 for individual participants on each of the 3 problems. Figure 5 shows the combined participant POS use of stimuli on each problem.

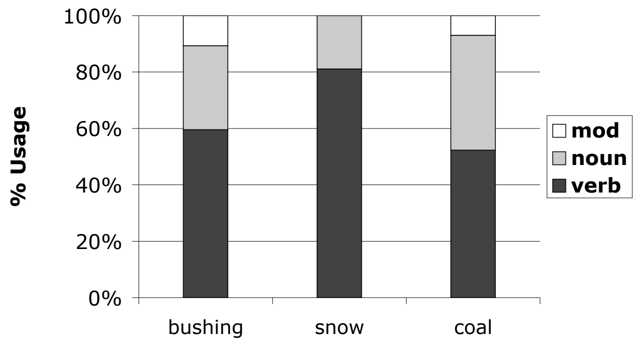

Figure 2: Participant 1 POS use of stimuli.

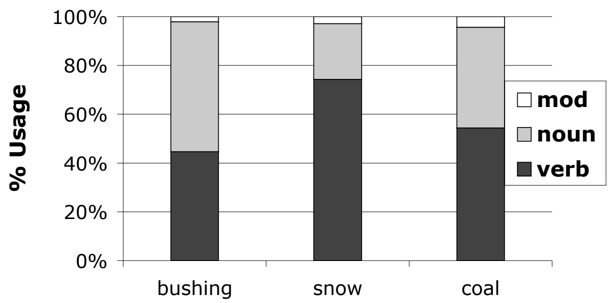

Figure 3: Participant 2 POS use of stimuli.

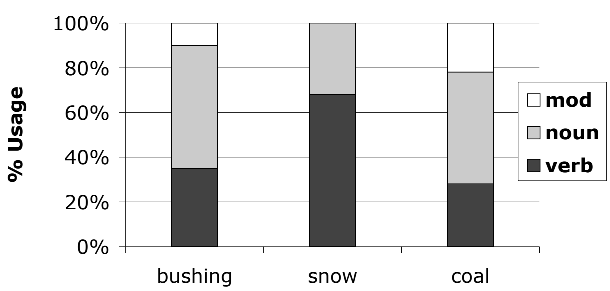

Figure 4: Participant 3 POS use of stimuli.

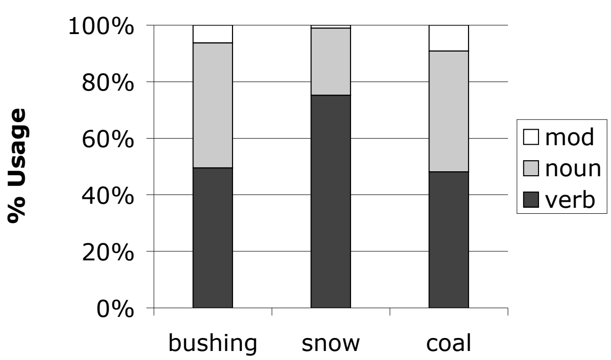

Figure 5: Combined participant POS stimulus use.

Table 5 shows overall stimulus usage with respect to the POS classes for each problem.

Table 5: Calculation of combined participant POS stimulus use for each problem.

	Verb	Noun	Noun mod.	Total	Verb %	Noun %	Noun mod. %
Bush-ing	56	50	7	113	49.6	44.2	6.2
Snow	73	23	1	97	75.2	23.7	1.0
Coal	79	70	15	164	48.2	42.7	9.1

5.3 Relationship between stimuli and other words and phrases

Next, using English syntactical rules, we examined how stimulus words related to other words and phrases produced by the participants. These other words and phrases are of interest because they represent ideas. These ideas can then be related back to the stimuli if they are introduced by the stimuli, e.g., if these other words and phrases are arguments of the stimuli. Depending on the stimulus POS, the introduced argument can be a single noun or verb, or an entire constituent phrase such as a noun phrase (NP), a prepositional phrase (PP) or a verb phrase (VP). Equations 1 through 4 below describe the structural relationships between the different constituents and words.

Equation 1: S -> NP VP
Equation 2: NP -> (art) N (PP)
Equation 3: VP -> V (NP)
Equation 4: PP -> P NP

where: S = sentence, NP = noun phrase, VP = verb phrase, PP = prepositional phrase, N = noun, V = verb, Art = article (e.g., "the"), and P = preposition (Akmajian et al., 1998). Parentheses denote optional constituents or words, showing that a single noun can constitute a noun phrase, for example. Equation 1 applies to clauses as well as sentences. In our study, participants typically uttered clauses, not full sentences.

As there is no terminal condition defined, a grammatical sentence of infinite length can be generated as follows:

S -> NP VP
S -> NP [V NP]
S -> NP [V [N PP]]
S -> NP [V [N [P NP]]] …

An example of such a sentence would be, "The students went to the store across the street in the city with green grass around the park...etc."

When stimuli were used as verbs, ideas can be introduced either as the noun phrase argument before the verb or the noun phrase argument after the verb. From a grammatical point of view, the noun phrase before the verb is a subject/agent/actor, while the noun phrase after the verb is an object. The possible arguments for each stimulus POS is shown in Table 6. Table 7 gives examples that illustrate cases enumerated in Table 6.

Table 6: Possible argument positions for stimulus POS classes. Arguments underlined, stimuli bolded italics.

Stimulus POS	Possible Arguments
1. verb	NP1 ***Stimulus as verb*** NP2 (PP)
2a. noun	***Stimulus as noun*** Verb NP
2b. noun	NP Verb ***Stimulus as noun***
3a. noun mod.	NP1 Verb ***Stimulus as noun mod.*** NP2
3b. noun mod.	***Stimulus as noun mod.*** NP1 Verb NP2 (PP)

Our definition of arguments for nouns and noun modifiers is different from the linguistic one where for nouns, arguments are either a possessive noun phrase before the noun, e.g., the guide's *contour*, or a prepositional phrase after the noun, e.g., *distribution* of coal (Jackendoff, 1983). Because we want to examine the verbs associated with nouns and noun modifiers, we extend the definition of "argument" to include verbs, in addition to the element immediately adjacent to the stimulus that is the linguistic argument.

For stimulus POS classes 1-2b, there are two possible arguments that could be introduced, e.g., for verb stimuli, noun phrase 1 (subject) and noun phrase 2 (object). For stimulus POS classes 3a and 3b (noun modifiers), there are three possible arguments for stimuli, e.g., NP1, NP2 and a verb. For cases 2a-3b, one of the possible arguments is no longer directly related or adjacent to the stimulus. For example, for case 2a where the stimulus is used as the first noun, the noun phrase following the verb is not directly related/adjacent to the stimulus. However, we still consider the entire construct of

S -> NP V NP

as possible arguments to investigate how the use of stimulus words leads to concept generation.

Table 7 illustrates each stimulus POS case using examples from transcripts of our study.

Table 7: Example of stimulus POS and arguments.

Stimulus POS	Stimulus Arguments
1. verb, *match*	You ***match*** the perpendicular surfaces.
2a. noun, *skew*	***Skew*** is the problem.
2b. noun, *reorient*	Adjust is ***reorient.***
3a. noun mod., *match*	Guides have ***matching*** contours.
3b. noun mod., *bottle*	***Bottle*** design ensures continuous supply.

The argument words and phrases represent ideas related to the stimuli. These arguments were found to contain ideas that are 1) not new; 2) not new but generally related to the problem or task; and 3) new. Argument categories are detailed below:

1. Not new: These arguments consist primarily of function words, words that are not content bearing, or words that are very common in the English language, e.g., "is", "have", "see", "think", "you", "me", "I", "we", etc. For example, the very common words "I" and "see" are arguments for stimulus word "match" in "I see the word *match*". Note that function words above refer to the grammatical term (see nomenclature), not the typical engineering meaning associated with the word function.
2. Not new, but generally related: These arguments consist of words and phrases given in the stimulus set, problem statement or are related to the problem solving process in general. While these arguments are related to the task at hand and show that the participant is generally attending to the task, they do not introduce new ideas, and include words such as: problem, solve, word, bushing, pin, etc. For example, the word "problem" is the argument for stimulus word "skew" in "*skew* is the problem."
3. New: These arguments consist of previously unseen words or phrases. Such arguments are not common words, repeats of stimuli or words from the problem statement. For example, "guide" and "surface" are arguments for stimulus "match" in "the guide *matches* the surface".

Only unique arguments were counted for each stimulus word. For example, if the stimulus "skew" used "problem" as an argument 5 times, then "problem" is only counted once.

Since arguments in categories 1 and 2 do not consist of new words or phrases, we assert that they do not introduce new ideas into the thought process, and thus do not assist in generating new concepts. Based on this assertion, we found that 36% of arguments introduced new ideas into the concept generation process (category 3 arguments), while 19.8% of arguments were generally related to the problem/task (category 2 arguments), and 44.2% of the arguments were not specific to the problem/task (category 1 arguments). Of the 36% of arguments from category 3 that introduce new ideas to the task, 23.6% (of 36%, or 65.5%) were verb arguments. Figure 6 shows the breakdown of the argument categories and associated stimulus POS classes.

Therefore, while stimuli are used in both noun and verb forms (with almost equal usage in the bushing and coal problems), arguments of the verb use of stimuli introduce the majority of the new words and phrases, and thus new ideas.

The importance of using verbs to introduce new ideas becomes more apparent when comparing the number of new arguments to the total stimulus use in each POS class, i.e., the total number of times stimuli were used as verbs, nouns or noun modifiers versus the number of new arguments introduced. This information is summarized in Table 8.

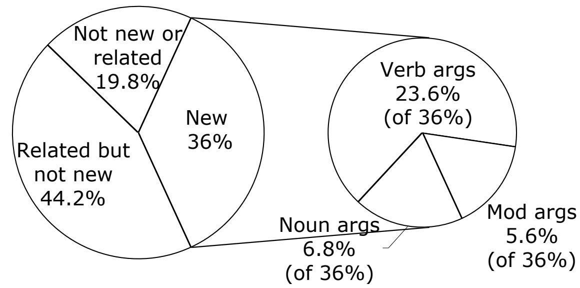

Figure 6: Argument categories and associated stimulus POS breakdown of new arguments.

Table 8: Proportion of new ideas introduced through arguments of stimuli for each POS class.

	Verbs	Noun	Noun mod.
1. New arguments	80	23	19
2. Total used	208	143	23
% = row 1/row 2	38.5%	16.1%	82.6%

Theoretically, it is possible that each stimulus used introduces at least twice the number of new ideas as the number of times used. This would require e.g., both the subject and object arguments for every verb use to be present, which was not often the case. While it was rare for stimuli to be used as noun modifiers, this class of use often introduced new ideas.

6 DISCUSSION

6.1 Development of concepts

The participants developed a total of 7 unique concepts from the stimulus sets. Two concepts each for the snow and coal problems were similar: Participant 2's "snow bricks" and Participant 3's "snow blanket" concepts, and Participant 1's "high heaps of coal" and Participant 2's "coal tower" concepts. The snow concepts shared "constrict" as a common stimulus word, however one participant expressed a desire to constrict the heat escaping the house, while the other wanted to constrict the snow falling on the house. The coal concepts were developed from different stimulus words, the noun use of "heap" and the noun use of "keep" as in "a medieval tower".

In the snow concepts, the participants' ability to supply different arguments to the stimulus "constrict", e.g., constrict heat escaping from the house versus constrict the snow, is one indication of the flexibility and the mutability of verbs (Gentner & France, 1988), where verbs can take on slightly different meanings depending on the noun arguments.

The coal concepts highlight the issue of homonyms, words that have the same spelling or pronunciation, but different meanings. While "keep" was intended in the verb sense of "continuing in the same state" as a hypernym of "to store", the use of "keep" as a homonym to mean part of a medieval castle did introduce a new idea. While we wish to use the ambiguity of words to help stimulate creative design, we are primarily interested in using words as controllable and related stimuli and not as unrelated stimuli. This suggests the need to address issues of homonyms and other personal, episodic associations.

In a previous pen-and-paper experiment, we also observed a number of different concepts, where the larger sample size allowed us to map specific stimulus words to concepts (Chiu & Shu, 2007b). Our previous and current work confirms that the same word stimuli can lead to a variety of concepts. The different concepts described here appear to follow some of the same trends reported earlier:

1. Higher-level, more general, words were often used in conjunction with lower-level, more specific words, and
2. Words that are more transitive, or have more senses that take direct objects, tend to be used more often in the development of concepts.

6.1.1 Word level

Participants 1 and 2 used "move" and "change" (higher, level-1 words) in conjunction with "constrict" (lower, level-3 word) in the snow problem. Participant 3 tended to use lower-level words only, e.g., "inject" (level 4) in the bushing problem. Dong (2006) noted that experienced designers use higher-level words more often, suggesting that experienced designers abstract more.

6.1.2 Transitivity

Verbs that often take a direct object appear to be better stimuli for the processes studied. Since design often involves manipulating objects (Simon, 1969), more transitive stimulus words may better support the process of acting on objects.

6.2 Stimulus POS classes and syntactical relationships

Examining results at the word-level showed that participants often used stimuli in forms other than the verb form intended, which was not revealed in past pen-and-paper experiments. In the bushing and coal problems, over half the instances of stimulus usage were in the noun and noun modifier forms. In part, this represents how participants reasoned about the stimulus words. For example, when examining the word "push", one participant expressed "*push* is like pull". Another participant expressed "I see the word *tighten*". In both cases, the stimuli were used as nouns. In addition to such meta-discourse, stimulus words were also used in noun form to refer to the actual referent that the word symbolizes. Examples include: "*skew* is the problem I wish to solve", "tolerance *matching*", "*supply* is the function of the coal pile" and "controlled *distribution*".

6.2.1 POS stimuli use between participants and problems

The participants showed consistent POS usage patterns of stimuli between the bushing and coal problems. Participants 1 and 2 used noun and verb forms about equally while Participant 3 used mostly noun forms. In contrast, all three participants showed noticeably more verb-form use of stimuli for the snow problem, at 75.2% averaged over the 3 participants. We speculate that the snow problem may be more abstract or novel to the participants, who had more academic opportunity to reason with problems in manufacture and assembly (bushing) and supply chain management (coal storage). While participants did use stimuli as verbs more often in the snow problem, the stimulus verb arguments did not introduce proportionally more new ideas. However, it is interesting that this problem resulted in more use of stimuli in the verb form.

6.2.2 Stimuli use in noun form

Overall, the high level of stimulus use in noun form, revealed by the word-level analysis, may confirm that people reason using objects. Many theories of meaning in language are "corporeal theories", where meaning is made by relating symbols to physical external entities (Whitehurst, 1979). One specific corporeal theory is reference theory, which suggests that the meaning of a word is the object that it represents to an individual. While this theory (and many other theories of meaning) is limited because it fails to account for abstract nouns, e.g., justice or relativity, this theory recognizes that people tend to reason with objects rather than actions.

When we consider syntax to extract relationships between stimulus use and stimulus arguments, nouns only introduced 16.1% of new ideas in their arguments, e.g., as a verb or other noun phrase. Many of the introduced verbs are function words, e.g., forms of “to be” or “to have” that describe states rather than actions. Stimuli used as nouns were often in the object noun phrase, where the associated subject noun phrase refers to the participant “I”, “we”, etc., thus not introducing new ideas.

6.2.3 Stimuli use in noun-modifier form

The proportion of new arguments resulting from stimuli used as noun modifiers was surprisingly high. While this accounted for only about 6% of stimulus usage, of the 23 times stimuli were used as noun modifiers, 19 new ideas were introduced by the arguments. Stimuli used as noun modifiers may introduce more new ideas because they have three possible arguments: the noun the stimulus directly modifies, a verb, and an additional noun phrase. However, only one participant introduced new ideas through two of the arguments. In the other cases, new ideas were introduced only through the single noun being directly modified by the stimulus. While noun modifiers are often nouns themselves (the noun “wool” rather than the proper adjective “woolen”), they appear to have some of the flexibility of verbs because they are used to describe another object rather than being fixed to the object itself. Adjectives, specific types of noun modifiers, are often viewed by modern linguistics as words that share properties with verbs or as an intermediate between verbs and nouns (Matthews, 1997). Adjectives are semantically more flexible than other POS (Marx, 1983) as well as syntactically more flexible as they can occur in many places. For example, the adjective “skew” occurs before the noun in “the *skew* problem” and as an argument to a verb in “the problem is *skew*”.

The rare use of stimuli as noun modifiers in our study may be due to the limited stimuli provided, thus restricting the construction of semantically appropriate noun modifier and noun combinations. Gagne (2001) reports that people can easily interpret novel and previously unseen noun-noun combinations and the corresponding combined concepts represented. Perhaps the ease of interpretation, once a valid combination is constructed from the limited stimuli provided, contributes to the high proportion of new arguments and ideas introduced by noun modifiers. However, their infrequent use suggests that it is more difficult to use stimuli as noun modifiers, which may limit their role as design stimuli.

6.2.4 Stimuli use in verb form

When stimuli were used as verbs, 38.5% of the verb arguments introduced new ideas, more than twice the rate for noun arguments. Most of the new ideas were introduced as the object noun phrase of the verb. Therefore, the stimulus verb often was used to act upon the argument, and rarely did a newly introduced argument act as the agent performing the verb action. The flexibility of verbs may have facilitated the use of new and complex arguments that introduced new ideas. Complexity in the noun phrase argument is generated through the recursive property of the noun phrase structure. In the previously presented infinite sentence example, it is possible to introduce an infinite number of noun phrases after the verb.

The complexity of the noun or prepositional phrase introduced depends on the participant. Participant 2 often used complex, nested noun or prepositional phrases while Participant 1 used fewer nested noun phrases, and Participant 3 almost never used nested noun phrases. Examples of noun phrases by Participant 2 include “you can *compress* it enough to snow ball consistency” and “I want to *constrict* the motion of heat”. The ease of attaching additional noun or prepositional phrases after a stimulus in verb form may thus encourage and facilitate the introduction of new ideas during the reasoning process.

Mabogunje and Leifer (1997) concluded that successful project groups produced more noun phrases in project documentation. Mabogunje (2004) chose noun phrases as the metric as they appear to change more over time, while verb phrases did not change by the same intensity, likely because verb phrases were fixed by the known functionality of the design. Our results suggest that designers use verbs to introduce new noun phrases that in turn represent new ideas.

6.2.5 Conclusion

Examining stimulus use at both word (POS) and relational syntax levels reveals that participants may reason with stimuli in their noun form, but arguments representing new ideas are introduced more frequently when using stimuli as verbs.

7 SUMMARY AND FUTURE WORK

Using verbal protocols, we were able to study how designers used word stimuli during concept generation. When the POS classes of stimuli used were examined, we found that participants would use the provided stimuli as verbs and nouns almost equally, even though all stimuli were provided in verb form. While this appears to confirm that people tend to “think in things”, it was hard to reconcile this with the functional approach to design (where verbs are emphasized) that motivated the presentation of stimuli in verb form. However, when relationships between stimuli used and other phrases produced by the participants were examined, we found that using the stimuli as verbs enabled the introduction of more new ideas than using stimuli as nouns.

Other results include the possible increased use of stimuli as verbs when considering novel or abstract problems. As verb use of stimuli is important to the introduction of new ideas to concept generation, this may facilitate the expansion of the solution space for such problems. A surprising result was that noun modifiers appear to introduce the highest proportion of new ideas, perhaps because they are similar to verbs in being more flexible than nouns. But, noun modifiers were used infrequently, suggesting they may be difficult to exploit.

Overall, this work suggests that using related semantic stimuli in the form of words related to keywords of the problem statement could be effective. Further understanding of the relationship between language and design will enable us to establish the foundation for an innovative language-based design-support tool for concept generation. Such a system will exploit the relationship between language and reasoning to support the concept generation process.

Future work includes investigating the use of word stimuli by more experienced designers, and comparing concept generation with and without word stimuli.

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