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IS A FIGURE-CONCEPT BINARY ARGUMENTATION PATTERN INHERENT IN VISUAL DESIGN REASONING?

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Abstract. This paper is based on the assumption that because designing is aimed at specifying configurations of entities, designers must manipulate forms and shapes and they must resort to visual reasoning to do so. Visual reasoning in designing is seen as the interplay between figural and conceptual reasoning, such that the one supports and continues the other in order to arrive at a configuration that is valid in terms of all the requirements it is to satisfy. We use protocol analysis to explore the bond between conceptual and figural reasoning at two levels of cognitive operation – that of the design move and that of the argument that is its building block. We conclude that the two modes of reasoning are equi-present in designing; they describe a binary system characterized by high frequency shifts between figure and concept.

1. Introduction

Is there such a thing as visual reasoning, as opposed to 'regular' reasoning? The question brings to mind the imagery debate, in which proponents defended, respectively, propositional *or* pictorial views of mental imagery (Block, 1981; Tye, 1991). According to Margaret Boden, all reasoning is of a kind, i.e. computational *tout court*, and attempting to single out visual reasoning is, in this view, futile at best[1]. That reasoning is not contingent on visualization is quite clear: many abstract concepts can be reasoned about with no recourse to visualization. However, when spatial configurations or two and three dimensional shapes and forms are the objects of reasoning, images are involved that must be figuratively represented to be reasoned about. Representations may be internal, as in mental imagery, or external, such as live and inanimate physical entities, or various kinds of drawings. In tasks that require communication with others, imagery is inadequate not only because of the inability to share it, but also due to its significant inherent limitations (i.e., inaccuracy, fast fading, etc.).

[1] Personal communication, Vienna, April 6, 1994.

Even in private, individuals very often feel the need to transcend and extend the representational powers of mental imagery by using external representations while reasoning in problem-solving. In designing[2], where one must by definition reason about properties of forms and shapes, imagery is commonly complemented, amplified and surpassed by using external visual displays, often self-generated in the form of drawings, especially sketches (e.g., Goldschmidt, 1991; Fish, forthcoming; Fish and Scrivener, 1990). We propose that that reasoning that is heavily reliant on figural representation may be termed 'visual reasoning', regardless of the medium of representation involved.

In this paper we are interested in design reasoning where visual displays in the form of sketches are commonly generated and contemplated in the process of preliminary design, as fortifications of internal imagistic representations. The observable wealth of sketching customs and habits, interesting in themselves, is immaterial to our current investigation in which we wish to assess the role of the figure, or pictorial image, in design reasoning. We shall propose a binary reasoning system in which the figure, representative of an aspect (or aspects) of the entity that is being designed, is constantly coupled with a validating concept, a rationale, or a raison d'etre. At the same time every concept, desire, or requirement is likewise matched with a figure – an illustration, instantiation, or example, represented externally or internally (in which case, we rely on verbal evidence. See the section on protocol analysis below). We shall show that the one has no existence without the other: there appears to exist a causal relationship between figure and concept, which is responsible for a nearly perfect balance between figural and conceptual arguments in design reasoning. We maintain that this balanced relationship is inherent in design reasoning.

2. Analyzing the Process of Designing: Moves and Arguments

When solving well-defined and well-structured problems, one is not expected to justify the solution that is reached; at most, one is asked to retrace one's steps, so as to explain how the solution was arrived at. The case of ill-defined and ill-structured problems, to which design problems belong is different. More than one solution is possible and sometimes a large number of very different solutions may be equally acceptable and similarly valued. When presenting a solution to a design problem one is always required to accompany it with a justification. The justification is

[2] *Design* in this paper refers to physical design only, such as architectural, industrial, or graphic design.

meant to establish the appropriateness and demonstrate the advantages of that particular solution vis a vis any number of other plausible solutions to the problem (which the problem-solver has not chosen to present although they may have been considered earlier in the design search). Because of the complexity of most design problems and the need to reach a good fit among the components of a design solution, it is almost impossible to postpone thinking of justifications until the entire design solution is in place. Rather, designers constantly look for congruence between their candidate solutions and partial solutions and corresponding design goals, requirements, and constraints. In other words, designers *reason* about the actions they take such that at any given moment there is a rational explanation for the goodness of those actions in terms of the coherence of the design search. Indeed, it would not be exaggerated to claim that design education, as carried out in the studio, is largely aimed at training students to so reason while engaged in designing. Acquiring the reasoning mode that is typical of designing is by no means a trivial feat. The difficulty dwells in the need to deal with a large number of issues in many different domains (e.g., in the case of architecture, climate, topography, functional needs, cultural values, structural requirements and many more) in the framework of one unified design solution. Within this framework, the rationale for every single response to a partial problem must be in good agreement with all other responses to the various other partial problems.

Sometimes an explicit request to specify the design rationale for accepting (or rejecting) a certain proposal is voiced (Ball et al., in press). For example, in a design session in which a bicycle rack is being designed, several ideas are being inspected; on one occasion, a team-member asks: "…should we like break down a rationale for our killing off some of these ideas…?". In another instance, a team-member asks: "[what is the] design rationale?"[3] Moreover, reasoning about designing is not an activity apart, which lies outside of designing and closely follows it: it is part and parcel of designing. Designing means generating and manipulating forms, shapes and configurations and reasoning about their properties in terms of their congruence with goals and requirements, both predetermined and those generated or modified on the fly. This notion is critical to our inquiry in this paper and we hope to clarify it in the sections that follow.

Once a design task is established, a problem-solving process is initiated in which solutions are sought while problems are being defined and framed. Since design problems are, as mentioned earlier, typically ill-defined and/or ill-structured, this process takes the form of a search. The search is conducted in a space which combines a problem space and a solution space

[3] These examples is taken from the 1994 "Delft Protocols" (Cross et al., 1996). See appendix 1, Delft team protocol segment 32, moves 6 and 59.

respectively, regulated by the design world in which the designer operates, i.e., prevailing cultural and professional norms, the designer's personal set of values, repertoire and skills, and the context of the task. The dimensions of the search-space are proportional to the degree of innovation and creativity of designing: with increased novelty, the space is extended and enlarged to encompass new explorations and solutions (Rosenman and Gero, 1993). Within the search space, the designer navigates by making design *moves*. A design move, analogous to a chess move, is an act that transforms the state of the design search in some measure. It may be, but does not have to be, a decision, nor even a tentative assertion; it may be a question regarding an aspect of the emerging design, a side comment, or a request for information. A move is the smallest perceivable and coherent unit of operation that the designer makes. The average duration of a move in one of our team work studies was 4.3 seconds; a move consists of between a few words and a few sentences (should speech allow detection and documentation - see the section on protocol analysis below). To get a better sense of what we are talking about, let us consider a move, verbally expressed, made by a designer who is part of the team engaged in the design of a bicycle rack for a backpack (quoted above; see note 3):

> "cos it would be nice I think I mean just from a positioning standpoint if we've got this frame outline and we know that they're gonna stick with that you can vacuum form a tray or a"

This move was identifiable because the designers were talking while working, and their verbalizations were recorded. Records of verbalizations during problem-solving (or other mental activities) are the basis of our analytic methodology - protocol analysis.

2.1. PROTOCOL ANALYSIS

Despite its limitations, protocol analysis is undoubtedly a most useful methodology for the study of short episodes of problem solving, in which the aim is to detect cognitive activity as authentically as possible by recording its reflection in verbalization. We use this methodology believing that it is indeed the best available gateway to an approximation of actual cognitive activity, and in particular problem-solving. When the problem-solvers are members of a team, and verbal communication occurs naturally, it is easy to record verbalization. When we deal with an individual, we must ask the problem-solver to 'speak out loud', in which case verbalization is induced artificially. In our own experience, and in that of others (e.g., Ericsson and Simon, 1984/1993; Gero and McNeill, 1998), this does not affect the reliability of the resultant verbal reflection of thought. We have responded to typical criticism of protocol analysis elsewhere (Goldschmidt and Weil, 1998), and it is our assumption that at present it is no longer necessary to defend this research methodology. The analyses we present in this paper are based on the Delft protocols and are supported by other protocol studies of several individuals in a number of design domains, all of whom talked while working and felt comfortable doing so. Since designers habitually sketch while designing, especially in the initial search phase, the sketches produced by our subjects were integrated into the protocols of their design sessions. Once transcribed, protocols are parsed into units of analysis. The choice of units is not predetermined but is established in accordance with the goals of the study in question, and the desired 'grain' of analysis. Our studies are conducted at two levels of analysis, with the design *move* and *argument* as the basic units into which protocols are parsed.

Most design moves are composite – they are made of smaller units of thought, which we call *arguments*. An argument is a single coherent statement that is syntactically complete, but does not necessarily reflect a move, or a design operation of any kind. Arguments are the building blocks of moves. Some succinct moves are composed of a single argument; others comprise several arguments, usually no more than two or three, and rarely more than five. The argument is our second, smaller unit of analysis (in our data moves by team members and by the individual designer comprise, on average, 1.50 and 1.74 arguments, respectively).

The move quoted above is composed of four arguments:

- cos it would be nice I think I mean just from a positioning standpoint
- if we've got this frame outline
- and we know that they're gonna stick with that
- you can vacuum form a tray or a

In what follows, we shall briefly discuss design reasoning at the level of moves, by way of introduction to a more detailed discussion of design reasoning at the level of arguments, in which we explore the relationship between the figural and conceptual modes of reasoning.

3. Design Reasoning at the Level of Moves: Consistency by Linkage

A typical design session in our experiments lasts between one and two hours. A protocol of such a session is divided into segments defined by the contents of the design activity and typically lasting a few minutes each. The nature of the study determines which individual segments are to be analyzed. A chosen segment is then parsed into moves: according to its length it may contain between approximately 15 and close to 100 moves.

In most protocol studies, the moves (or other units of analysis) are then coded using a scheme of categories that the researchers determine as per the objectives of the study (e.g., Gero and McNeill, 1998; Purcell, Gero, Edwards and McNeill, 1996).

In our case, we are interested in the question: how does the designer construct the design rationale, its justification, as part of the design search? Given that the design problem is ill-defined, we must assume that the search is wide and fairly unstructured, and that the designer may resort to information from totally unpredictable sources, in any domain at all, and in a sequence that may be highly random, to reason about the emerging design. In the early phases of the search the designer may be considering several solution directions; much of what is being considered is tentative and may be dropped in favor of more promising solution directions. Therefore, our interest dwells in the mechanisms of reasoning rather than in the categories of information, and we do not code the moves. Instead, we establish links among sequences of moves in the segments that are being analyzed, and notate them in *linkographs*. Links are determined by the researcher on the basis of the contents of moves, using common sense to decide the existence of a link or its absence. For each move, as of the second, we ask the question: is there a link between this move and any of the preceding moves in the segment that is being analyzed? For the n^{th} move, the question is therefore asked n-1 times, and this is also the maximum number of potential *backlinks* we may establish and notate. The links we notate are backlinks, because we look back at earlier moves to establish their existence. Once we have notated all the links, we can also determine, after the fact, *forelinks*, or links between a move and posterior moves (which have backlinks to that specific move). We, and others, have written about linkography and its uses elsewhere (e.g., Cross, 1997; Goldschmidt, 1996; Goldschmidt and Weil, 1998; van der Lugt, 2000). Here we would only like to emphasize the principle behind linkographic studies, namely the ability to observe how designers reason about what they are doing. We are able to show that designers are constantly ensuring that tentative assertions are associated with all aspects of the design that may possibly be relevant to its success. They do so by interlinking their moves as densely as possible, to create a tightly knit mesh. Let us return to the move cited earlier (move 32), and inspect links among it and other moves in the same segment, made by members of the design team. These links are presented in Table 1.

In this example move 32 has two backlinks, formed with the immediately preceding moves (in some cases links are formed with 'remote' moves, further back in time). Once all the backlinks of moves in this segment (68 moves in all) are notated, we discern that move 32 also forms eight forelinks. The number of links that move 32 forms is high –

most moves generate a lower number of links. We can calculate the average number of links per move in every segment we analyze – this number is its Link Index (total number of backlinks + total number of forelinks divided by twice the number of moves). The Link Index for the segment we are looking at is 2.99 (i.e., the average move generates a total of nearly 6 back and fore links, as opposed to 10 links in the case of move 32). The common denominator that connects move 32 to the two moves that were made earlier and to the eight moves that would link to it later is the *tray*. All the moves address the idea that the bicycle rack that is being designed would resemble a tray. Advantages of the tray metaphor are pointed out: it takes care of hanging parts of the backpack which is to be placed in it, like its straps and possibly a sleeping bag ("rooster tail"), and it can be vacuum-formed (which is inexpensive). Means of securing the backpack to the tray are also considered. Interestingly, the designers felt no need to explain why a tray-like shape effectively contains loose parts: it was tacitly taken for granted that a tray embodies a rimmed surface and that the rim is responsible for holding straps etc. in place (inner representations are likely to have been constructed).

This example illustrates the pattern of dense move interconnectivity that is typical of the regular progression of the design process. Experienced designers almost never generate design moves that are not linked to other moves. Making sure that a network of links governs sequences of design moves is a hallmark of expertise in design behavior. Design consistency and coherence are achieved by linking every step the designer makes with relevant information that has already been, or can be, elicited (verbally in this case), so as to assess that step's potential contribution to a candidate solution to the design problem. Although our experimental data is limited in scope, we believe in the robustness of our findings in the examples we have analyzed, namely that linkability among design moves (as measurable in terms of Link Index) is closely correlated with expertise: the more experienced the designer, the higher the Link Index (e.g., Goldschmidt, 1996). We would go as far as postulating that acquiring design skills involves the attaining of fluency in reasoning by linking design moves to one another in the manner outlined here.

TABLE 1. Links formed by a move

Links	Move#	Protocol
	32	cos it would be nice I think I mean just from a positioning standpoint if we've got this frame outline and we know that they're gonna stick with that you can vacuum form a tray or a
Backlinks	30	so either it's a bag or maybe it's like a little vacuum formed tray kinds for it to sit in
	31	yeah a tray that's right OK
Forelinks	33	Right and even just a small part of the tray or I guess they have these
	35	Maybe the tray could have plastic snap features in it so you just like kkkkk snap your backpack down in it
	37	It's a multifunction part huh
	40	It takes care of the easy it takes care of the rooster tail problem of your pack
	42	Maybe it could be part maybe it could be a tray with a net and a drawstring on the top of it I like that
	50	So what we're doing right now though is we're coming up with like again classifications of solutions of kind of all they're all either or things I mean like I wouldn't do the net and the shade and the snap in with the tray either or any one of those will probably
	54	I think tray is sorta a new one on the list it's not a subset bag it's kind of er yeah but oh yeah yeah yeah oh I see shade straps is how do you dress the straps on the back
	64	You have a the tray would zip clip

Since we have avoided their classification, we know little about the nature of moves; but the examples that Table 1 provides suffice to convince us that moves are a mixed bag indeed. If we returned now to our claim that design reasoning is based on interlinking moves because proposed design solutions are created in concert with their rationale, their justification or their raison d'être, we might want to know a little more about the moves. After all, the system of reasoning we described may be quite universal, and not necessarily specific to designing, or even to visual reasoning in general. It is fine to base links on a common-sense scrutiny of their contents, but is this contents of no consequence? Should we not take the move's contents apart to see what it actually consists of, and what in it may be unique to designing? Many moves are complex, often composite: we shall therefore go to a finer grain of analysis, that of arguments, to continue our quest into the mechanisms of design reasoning.

4. Design Reasoning at the Level of Arguments: Figure and Concept

Let us return to move 32, which, as we have already noted, is composed of four arguments. Are these arguments all of a kind? If we suspect they are not, what criteria should we use to differentiate them? Keeping in mind that we wish to concentrate on what distinguishes design reasoning from 'regular' problem-solving reasoning, we now bring into the analysis the *visual* quality of design activity and reasoning. In the kinds of design we address in this paper, the objective of the process of designing is to come up with at least one design proposal that ultimately specifies the designed entity in terms of its form(s) and function(s) at a certain level of precision and detailing. As discussed earlier, the proposal is – when presented - accompanied by its rationale, stressing the advantages that should make us prefer it to other plausible proposals. Since the rationale is being built up step by step as the process of designing moves along, it is logical to assume that reasoning about the form of an entity that is being designed speaks to that tentative form. It does so while sorting out its properties and examining their compatibility with the functioning of the entity and other requirements and wishes (e.g., cost effectiveness, ease of manufacturing, novelty, aesthetic value, cultural significance, and so on). Moreover, the process is not linear and en route designers often generate alternative ideas and candidate solutions and partial solutions, which they explore and reason about before accepting or rejecting them. The question we ask is therefore: is there a discernable pattern of design reasoning, in terms of the arguments that are being voiced? In particular, we would like to know how arguments concerning form relate to other arguments, those holding the rationale for choosing a form, explicitly and implicitly. We propose the following taxonomy of design argument modalities:

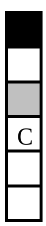
- ***Figure (F)*** Arguments of this modality directly address physical properties of form or shape, usually, but not always, as represented in a figure drawn (sketched) on paper as part of the design activity.
- Figure/Rationale (FR) In these hybrid arguments, Figure and Rationale cannot be pulled apart (at a finer grain of analysis, which is not attempted here, it should be possible to subdivide them into the two

parent modalities). We acknowledge these arguments and include them in our analyses.

- ***Rationale (R)*** Arguments of this modality present a direct rationale for favoring or rejecting specific forms or physical objects with specific properties.
- ***Comment (C)*** These arguments are general statements that cannot be seen as direct expressions of rationale, but which are part of the discussion regarding the designed entity or design in general.

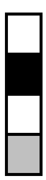
On rare occasions, we come across verbalizations that cannot be considered design arguments, such as jokes, general statements or incomplete expressions (e.g., "whatever the tray"). They are not acknowledged as arguments, and we code them as '***Not an Argument***'. When there is no agreement among coders regarding the modality of an argument, no modality can be assigned[4]. Such arguments are termed '***Not Decisive***'.

We thus have a scheme of modalities with which we code our protocol segments. To emphasize the sequencing of modalities we use the following graphic system:



Argument modality: Figure
Argument modality: Rationale
Argument modality: Figure/Rationale
Argument modality: Comment
No decisive modality
Not an argument

Accordingly, the arguments in move 32 are coded as follows:



cos it would be nice I think I mean just from a positioning standpoint
if we've got this frame outline
and we know that they're gonna stick with that
you can vacuum form a tray or a

The first argument in this move gives a rationale: the tray outline is positive ("nice") from a *positioning standpoint*. The second argument is figural: it pertains to the (rack's) *frame outline*. The third argument gives a rationale again: the client ("they") is going to accept this solution ("stick with that"). Why this certainty? Because, says the hybrid fourth argument, the tray can be manufactured inexpensively (vacuum formed). This

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[4] Unless otherwise noted, codes are assigned by three coders; when at least two coders agree on the same coding, it is assigned. See appendix 1.

argument is of the Figure/Rationale type because the figure of the tray is present in it along with an economic rationale for using it – the fact that an inexpensive manufacturing mode can be used to produce it[5]. The 68 arguments of the segment from which move 32 is taken, along with other segments from the Delft protocols, have been coded using this system of modalities and are presented in appendix 1.

4.1. FIGURE - CONCEPT

We shall remain with the Delft Protocols and use them as an exemplar: we have coded two sequences of arguments made by the team and two by the individual (see appendix 1). Table 2 summarizes the argument modality distribution in the four segments we have inspected. As the table shows, we have subtracted from the total number of coded arguments those coded 'Not an Argument' and those not assigned a decisive modality - both very small in number. For further analysis, we use the operative totals rather than the absolute totals (e.g., see Table 3 below). Note that in the segments in question the team makes twice the number of arguments made by the individual. In teamwork, where natural conversation flows fast, design moves tend to be significantly shorter than in individuals' think-aloud verbalization[6]. The speed of production, however, has no proven effect on the nature and pattern of reasoning. The number of arguments is, in both cases, sufficiently large to qualify as a statistically valid sample of the phenomenon we are investigating.

TABLE 2. Argument modality distribution

Segment	F	R	FR	C	Operative Total	Not an Argument	Not Decisive	Total
T-32	47	25	16	13	101	3	2	106
T-37	50	12	18	15	95	1	1	97
I-19	31	6	3	32	72	1	1	74
I-23	15	9	3	6	33	2	0	35

T = Team; I = Individual

[5] While moves 31 and 32 were made, the word 'TRAY' was added to a checklist on a whiteboard but no sketching took place. A sketch describing the tray (holding the backpack, with the bent tubes with which it was to be attached to the bicycle) was first made 12 minutes later. The figural component of this argument therefore reflects an internal representation.

[6] In the segments analyzed here, team-members generated an argument every 2.66 seconds, whereas the individual took 6.66 seconds to produce an argument.

We now combine these modalities into two main groupings: Figural and non-figural. The figural grouping consists of all the arguments of the Figure modality, and of half the arguments of the Figure/Rationale modality. The non-figural grouping, which we refer to as Conceptual, comprises all the arguments of the Rationale modality, half the arguments of the Figure/Rationale modality, and all the arguments of the Comment modality (see Table 3). Assigning an equal number of FR arguments to each grouping is based on the assumption that statistically they bear the same affinity to both groupings. Comments, which are a diverse lot, pertain to the Conceptual grouping primarily because they cannot be seen as Figural. The conceptual grouping, then, is more diversified than the Figural grouping.

We now repeat our hypothesis, as presented at the outset (end of the introduction): there is a nearly perfect balance between figural and conceptual arguments in design reasoning. In terms of our coding of arguments, the hypothesis translates as follows: no significant difference exists between the number of arguments of the Figural grouping and the number of arguments of the Conceptual grouping.

To test this hypothesis we compare the two groupings once for the team and once for the individual. As Table 3 shows, the team makes on the average 58.2% Figural arguments and 41.8% Conceptual arguments and since $p>0.05$, we conclude that for the team our hypothesis is confirmed. The individual designer makes 46.7% Figural arguments and 53.3% Conceptual arguments and since $p>0.05$, we conclude that for the individual, too, our hypothesis is confirmed, this time with even more confidence.

These results confirm that in the design sessions we have analyzed, for every figural argument a designer makes, regardless of whether the work is carried out individually or in a team, a conceptual ‘counter argument’ is also advanced. The opposite is also true: for every conceptual argument voiced, a figural counterpart argument is brought forth. In other words, arguments of both groupings even each other out. We have obtained similar results in other studies concerning shorter protocol segments of architectural design sessions (Goldschmidt, 1991) and graphic advertisement design (unpublished), as well as a shorter sequence from the Delft protocols (Goldschmidt, 1997)[7].

[7] In these studies a single experimenter coded the arguments. As mentioned earlier, in the current study three coders determined the final assignment of codes.

TABLE 3. Argument modality groupings (%)

Segment	Figural F+_FR	Conceptual R+C+_FR	Total	
T-32	54.5%	45.5%	100% (101)	
T-37	62.1%	37.9%	100% (95)	
I-19	45.1%	54.9%	100% (72)	
I-23	50.0%	50.0%	100% (33)	
Team Average	58.2%	41.8%	100% (196)	p = 0.067 (calculated with %)*
Individual Average	46.7%	53.3%	100% (105)	p = 0.242 (calculated with %)*

T = Team; I = Individual
* $p \geq 0.05$ means there is no significant difference between the types of groupings

We have established that designers make an equal number of figural and conceptual arguments, but this in itself does not yet certify that conceptual and figural reasoning are inseparably enmeshed in designing. One could theorize that a designer might first manipulate a configuration and only once it has been brought to a certain degree of completion, one looks for supporting concepts for it. Or conversely, that a designer could possibly work on specifying all the requirements that a not yet existent configuration should satisfy, before generating that configuration. It is sufficient to glance at the sequences of arguments in appendix 1 to realize that not even the slightest shred of evidence exists in support of such a theory. The longest string of sequential arguments of the same grouping contains 13 arguments (moves 4-7, Team segment 37, in which 12 arguments are coded F and one FR). This sequence, generated over 35 seconds, is exceptionally long. Most sequences of same grouping arguments are much shorter (interestingly, practically all longer strings of same grouping arguments are figural. Since most sketching activity accompanies the generation of figural arguments, a possible explanation of the inequality between figural and conceptual arguments in long string generation may have to do with the length of time necessary for the production of sketches). Sequences of same grouping arguments vary in length, then, from 1 to 13 (sequences of same *modality* arguments are shorter; the longest includes 8 arguments).

If we had found long strings of arguments within which groupings regularly shift from figural to conceptual and vice versa, we would have taken this to prove our claim that the two modes of reasoning are inextricable. This is not quite the case, although shifts in modality and grouping occur very frequently in our samples. We shall have more to say about shifts in modality and grouping in section 5.

5. Figure-Concept Shifts

Assuming that our data is typical of habitual design behavior, we have shown that in the course of a design search designers generate an equal number of arguments pertaining to figural and non-figural groupings. We also have indications that frequent shifts among these types of reasoning occur. We now wish to concentrate on shifts of both modalities of arguments and types of groupings, and we shall do so at the levels of arguments as well as moves. We return to moves because unlike arguments, which are complete entities syntax-wise, moves are also semantically complete entities. We would like to know with what kinds of arguments moves are initiated: what modalities are involved and consequently: is there a balance between moves starting with figural and conceptual reasoning? Table 4 presents the data pertaining to the modalities of arguments at the heads of moves, and Table 5 shows how this data is translated into figural and conceptual beginnings of moves. The results prove that in the case of the individual, we get the same number of figural and conceptual beginnings of moves. The team is less ‘perfect’: there is a slight but statistically significant difference in favor of figural arguments at the beginnings of moves.

We therefore conclude that moves, which are logical entities, have an almost equal chance of beginning with figural or conceptual type reasoning. But as in the case of argument modalities, we still do not know how these beginnings are distributed. Appendix 2 is a graphic representation of moves, classified by the grouping to which their first argument belongs. It illustrates vividly that with few exceptions, shifts in grouping types are very frequent. We can count these shifts, as well as the shifts in argument modalities as inferred from appendix 1. Table 6 summarizes these counts[8], using a Shift Index (S.I.), a figure obtained by dividing the number of shifts in a given segment into the number of relevant units, i.e. arguments or

[8] In appendix 1, arguments with no decisive modalities are ignored. In appendix 2, shifts are counted at the head of moves beginning with FR, but not at the beginning of the directly subsequent moves.

moves (we selected this indicator because of its affinity to the Link Index; see section 3).

TABLE 4. Argument modality at heads of moves

Segment	Moves starting with F	Moves starting with R	Moves starting with FR	Moves starting with C	Operative Total*
T-32	33	15	9	7	64
T-37	30	8	12	11	61
I-19	20	4	2	16	42
I-23	8	6	2	3	19

* Operative total leaves out single-argument moves coded Not an Argument or Not Decisive

TABLE 5. Argument modality at heads of moves (%)

Segment	Moves starting w/ Figural	Moves starting w/ Conceptual	Total	Sketching Status
T-32	58.6%	41.4%	100% (64)	No sketching on paper; use of whiteboard
T-37	59.0%	41.0%	100% (61)	First ensemble of 'tray', backpack and support
I-19	50%	50.0%	100% (42)	Transition – old idea is scrapped; new idea developed on new sheet of paper
I-23	47.4%	52.6%	100% (19)	Idea being developed – 'feature' introduced
Team Average	58.8%	41.2%	100% (125)	p = 0.044 (calculated with %) *
Individual Average	49.2%	50.8%	100% (61)	p > 0.05 (calculated with %) *

T = Team; I = Individual

* $p \geq 0.05$ means there is no significant difference between the types of groupings

TABLE 6. Shift index, argument modalities and groupings at heads of moves

Segment	S.I. Modalities of Arguments	S.I. Groupings of Heads of Moves
T-32	0.65	0.44
T-37	0.48	0.36
I-19	0.44	0.36
I-23	0.49	0.53
Team Average	0.57	0.40
Individual Average	0.47	0.44
T + I Average	0.52	0.42

T = Team; I = Individual

In the best of all possible design worlds, under our original assumption of a perfect causal relationship between figural and conceptual reasoning instances, we should obtain S.I.=1.0, which would mean a shift every time a new argument/move is generated. But since design worlds (not unlike all other worlds) are not perfect, we do not obtain this value for the Shift Indexes we have calculated. If we look at average values, our overall Shift Index is almost S.I.=0.5, meaning that roughly every other unit of reasoning comes into the world after the designer has switched his or her attention from figure to concept, or vice versa.

We have now established the rhythm at which figural and conceptual entities of reasoning are generated. We have an opportunity to compare our findings with those of a study by Akin and Lin (1996) that is based on the same Delft protocols that provided our data (individual designer). In their study, Akin and Lin developed an activity-based model of the design process. The coding categories abstracted the types of activity the designer was engaged in into three main groupings: Examining, Drawing, and Thinking[9]. The duration of each activity was measured and for the three activities was on average 25.4, 22.2, and 19.8 seconds respectively. Activities were carried out unaccompanied, or in overlap with one or two of the other activities. The most intriguing cases where those Akin and Lin call “triple-modes”, i.e., where all three activities occurred simultaneously.

[9] We have reservations concerning the differentiation between these activities, but we report Akin and Lin’s study in the spirit in which it was undertaken.

Such intervals were longer and lasted 35.26 seconds on average, which is the equivalent of 5.3 arguments, or 3 moves, in our study (individual designer). Then they identified all instances in the protocol in which design decisions were made (hundreds of decisions), and singled out some as Novel Design Decisions (NDD). In the main portion of the protocol they found 8 such NDDs. Design Decisions were then correlated with the findings regarding activities. The correlation showed that NDDs occur "while triple-mode activities are almost exclusively present" and statistically, this correlation's probability is shown to be beyond pure chance (ibid., 57-58). Although Akin and Lin's work has different goals than ours, and their results cannot be directly mapped onto our concerns, it seems possible to conclude from their work that hybrid reasoning in designing, i.e. simultaneous multi mode (triple, in their taxonomy) reasoning, is crucial for significant (novel) design progress. The activity modes they stipulate, Exploring, Drawing and Thinking can be seen as roughly reminiscent of our figural and conceptual argumentation or reasoning.

Although the grain of analysis in the two studies is different – we work at a finer grain (the argument is shorter than any of the units used by them in terms of time-span) – we still may, using appropriate caution, conclude that Akin and Lin's findings support our basic hypothesis. Akin and Lin recorded two NDDs in the time span that corresponds to our segment 23, and no NDD in what is our segment 19. We can confirm, based on previous studies, that the individual designer made an important breakthrough in segment 23 (Goldschmidt, 1996). If we now direct our attention to the S.I.s in Table 6 we notice that indeed, segment 23 has a much higher S.I., compared to segment 19. This may indicate that the S.I. value goes up with the rigorousness of the design search and its productivity (see also Goldschmidt, 1991). In other words, the frequency of shifts in reasoning mode may be a good indicator of a productive process of design problem-solving. The figure-concept bond, then, is not only ubiquitous in design reasoning, but its strength, as measured by shift frequencies, joins indicators like the the frequency of links among moves in assessing the quality of the design process.

6. Conclusion

We have shown that a Figure-Concept bond permeates design reasoning at all levels. Designers generate equal numbers or figural and conceptual arguments, and similar numbers of moves start with either mode of reasoning. Furthermore, we have shown that the design search is characterised by frequent shifts between figural and conceptual arguments and we find similar frequent shifts at the heads of moves. These findings are in line with numerous studies in several domains, which stress the faculty of visual reasoning and its importance in tasks that require the manipulation of forms and shapes (even in literary thinking; see for example Stern, 2000).

Is it useful to look at the emerging pattern we outlined as a binary reasoning system? We think this is a reasonable option, because if may allow us to model the *process* of design (as opposed to the product) in ways that enable classification and prediction of factors of its productivity and success. The computational implications of formal models have not been investigated, but we believe it is possible and worthwhile to proceed in this direction.

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Appendix 1. Argument Modalities (Delft Protocols)

Arguments - Delft team protocol, segment 32

■	Argument modality: Figure (N=47, of which 33 at head of move)
□	Argument modality: Rationale (N=25, of which 15 at head of move)
▒	Argument modality: Figure/Rationale (N=16, of which 9 at head of move)
C	Argument modality: Comment (N=13, of which 7 at head of move)
⧄	No decisive modality (N=2, of which 1 at head of move)
☒	Not an argument (N=3, of which 3 at head of move)
	M=Move; Ar=Argument; D=Designer (team member)

M	Ar	D	Protocol
1	☒	K	pack to rack
2	☒	I	joining concepts [J: yeah I think if we K: yeah]
3	□	J	I think if we do the joining concepts
	□		that might help us make some of our materials decisions too sort of
4	■	I	right OK Velcro [J: em I think if if]
5	▒	K	it wears out
6	□	J	yeah and if you're gonna have dirt and stuff in it
	□		should we like break down a rationale for our killing off some of these ideas too
7	C	K	nah no
8	C	I	we'll just say it and they'll record it
9	☒	I	em gravity gravity
10	□	J	er well up here in bumpy terrain
11	C	I	OK fix this
12	□	J	I mean maybe it can be part of the solution but[I: yeah]
13	■	J	snaps
14	□	J	depends on what kind
	■		if it's like snapson cloth em you know
	■		like those little Stimpson em press in [I: mm mm]
15	■	J	like rivet kind of snaps
	□		I don't particularly care for them
	■		but if it's like Fastex kind of snaps
	□		those are reasonable [I: mm mm OK]
16	▒	J	cos then you could cinch your backpack down too
	▒		you know nice compression straps
17	■	I	OK bungees
18	■	K	compression straps that also snap
19	■	I	that's bun- that's bungee like
20	■	J	straps with snaps
21	□	I	OK so now we're talking about the pack OK

			good quarter turn fasteners [K: err]
22		J	err there's something real positive about them
			but maybe uh I dunno we'll let's not cut them out yet[I: OK]
23		K	they're fast yeah
24		I	drawlatch
25		K	that's good for cinching down the load yeah[J: yeah]
26		I	well we sorta have that in the straps
27		K	so do the straps
		I	so we would do it as a strap way OK so
28	C	I	we'll just call it that for now
			er bag put it in a bag we're gonna need some sort of thing
			to do something with those straps
29		K	to get this out of the way [J: yeah I: yeah either the]
30		J	so it's either a bag
			or maybe it's like a little vacuum formed tray kinda
		J	for it to sit in
31		I	yeah a tray that's right OK
32		J	cos it would be nice I think I mean just from a positioning standpoint
			if we've got this frame outline
			and we know that they're gonna stick with that
			you can vacuum form a tray or a
33		I	right or even just a small part of the tray or I guess they have these
34		K	so something to dress this in [J: yeah I: or even just em]
35		J	maybe the tray could have plastic snap features in it
		I	so you just like kkkkkk snap your backpack down in it[I: mmmm I was thinking of er]
36		K	snap in these rails
37		J	it's a multifunction part huh
38		K	you just snap in these rails
39		J	yeah snap the rails into the tray there [K: mmmm I: OK]
40		J	it takes care of the easy it takes care of the rooster tail problem of your pack
41		I	uh uh what if your bag were big er
			uh uh what if your bag were big er
			but like a big net
			you just sorta like pulled it around and zipped there I dunno
42		J	maybe it could be part maybe it could be a tray with a with a net and a
			[cont'd] drawinstring on the top of it
	C		I like that [I: yeah I mean em]
43	C	J	that's a cool idea
44		I	a tray with sort of just hanging down net
			you can pull it around and and zip it closed
45		K	it could be like a a a window shade
			so you can kinda it sinks back in so it just [J: oh yeah]
46		I	it retracts yeah

47		K	you pull down it retracts in
48		J	a retracting shade [I: right right]
49		K	so that that's not dragging in the spokes
			if you don't have anything attached
50		J	so what we're doing right now though is we're coming up with like again
			[cont'd] classifications of solutions of kind of
	C		all they're all either or things
			I mean like we wouldn't do the net and the shade and the snap in with the tray
			either or any one of those will probably [I: yeah OK]
51		K	a net can be combined with the shade
			I mean you could have a retractable net
			that that's how I thought of it
52		I	so we I think the issue that we're talking about is is straps
	C		so we'll just keep that one on the burner
53	C	K	yeah maybe there's some cool innovation there [J: well yeah OK I: OK now
			[cont'd] er it had er has er]
54		J	I think tray is sorta a new one on the list
	C		it's not a subset of bag it's a kind of er yeah but oh yeah yeah yeah
			oh I see shade straps is how do you dress the straps on the back
55		I	yeah yeah OK ooooh legs up internal frame
	C		now what did that mean I think that meant er
56		J	oh that if you had legs off of the internal frame [I: yeah]
57		J	I think we decided we want to take the weight off of the pack
	C		so let's kill that guy
58		I	OK backpack straps
		I	using those we have a manikin in the back
59		J	design rationale
60		I	em big zipper in the back doing it er
			why don't we weed out one of these er zipper
61		J	I think a zipper could be
62		J	comes along the top of the tray or whatever [I: yeah]
63		K	that kinda goes with a bag bag on a tray
64		J	you have a the tray would zip clip [I: OK]
65		J	net or
66		K	zip clip net
67	C	J	what else did you suggest you suggested something different from that I think
68		I	clip net bungee draw

Arguments - Delft team protocol, segment 37

- Argument modality: Figure (N=50, of which 30 at head of move)
- Argument modality: Rationale (N=12, of which 8 at head of move)
- Argument modality: Figure/Rationale (N=18, of which 12 at head of move)
- C Argument modality: Comment (N=15, of which 11 at head of move)
- No decisive modality (N=1, of which 1 at head of move)
- Not an argument (N=1, of which 0 at head of move)

M=Move; Ar=Argument; D=Designer (team member)

M	Ar	D	Protocol
1	C	J	Where are we supposed to be schedulewise
	C		we're supposed to be designing right
2	C	I	yeah well that's what we're doing right [J: and OK]
	C		I think we should be done in about er
3		J	well OK well we know we like this tray idea right [I:right]
4		J	and and I guess if I had to express that someway I would
			I would see it as being something like er here's the front of the frame
			and there's the backpack sitting like this
			oops I guess I've got that backwards sorry the frame went backward now
			because we're gonna have the bedroll off the back
			so it's probably open at the rear [I:mm mm]
5		K	for the bedroll to stick out
6		J	for the bedroll to stick out it's kind of
			but there maybe a tray on the side
			I liked your idea of the netting thing too[K: mm mm]
7		I	you can know the tray could just have two punch holes
			for the bungee to go over it
			I think it'd just collecting the sides
		J	what bungee
8		I	to hold the backpack down
9		K	the straps cintch down to that
10		J	I'm just thinking that maybe maybe it's like em a one of those breathable nets
			[cont'd] type things [K: yeah]
11		J	that has a drawstring on it
12		I	oh one that expands
13		J	yea exactly exactly this way you can compress all this stuff down on your pack
14	C	I	well that it'll be we may get into a costing sheet but yeah
15		J	and then Kerry's got the OK we'll assume Kerry's tubes or can it be a single tube now
			can it just be like a tube that does this that's folded one time like this[I: oh yeah]
16		K	I think we want more than one
			we want two two to three like the Blackburn just because I bet they've done the
17		I	right there's no need in er reinventing that wheel[J: so OK]

			once they've patented it
18		K	they've got some that are two but their mountain bike ones tend to have three like this is
19		J	so to distribute like [K: mm mm]
20		I	yeah it's for strength and stiffness
21		J	and then er in this tray if we assume the tray could be injection moulded
			cos that seems to be within our cost targets these
22		I	oh the the injection moulding then would have the mounting feature up front
			[cont'd] whatever that is [K: mm mm]
			whatever the tray
23		J	and this could just have little snaps to the er er these rails
			so that to these tubes
			so we have this folding down spec
			so that if this junc(tion) point here had a pivot at it
			and and then it's kinda like you're folding TV trays
			you just unclip this guy from here and you unclip
			well you probably don't need to unclip the back one you just unclip one of these
			and then you can swing the legs flat [I: what what]
24		K	what the rack has to fold
25		J	yes the rack has to fold
26	C	K	where does it say that
27	C	J	it says that in our spec [I: where K: our spec J: says right here]
28	C	K	should fold down or stacked away easily[J: right so just]
29	C	K	what does that mean stacked away [J: oh OK]
30	C	I	OK I see I see your point
			so this goes up and the whole thing falls down
			you put it in the closet and it's flat so that's flat [J: right K: mm mm I: OK good K: OK]
31	C	I	no makes sense like a very good wine
32		J	very very actually what you could do is you could get it so that
33		I	that's that's probably held in a pivot
34		J	if you got it you unclip this
			then then you could flip this off around
			and it could sit inside the tray when you store it away[I: oh yeah K: yea that's it]
35		I	or look they went with the if you go with the big fat tube instead of that little skinny stuff
			you could probably get away with one tube
			and then you just do the same concept that they've done there
36		J	that that's what I was kinda drawing here was this this is a continuous tube
37		I	one big fat one [K: mm mm]
38		J	and then here's another
39		K	support
40		J	continuous tube
41		I	OK now we have to do a pivot [J: oh]
42		I	so we can get rid of this
43		J	by just making this beefy enough [I: yeah]

44	C	J	have to put a 'do not sit on this'
45		I	let's see now we're gonna say this comes off and we have your big er
46		K	knobby
47		J	knobs for quick release
48		I	we're gonna need them here too
49		K	mm mm four knobbies
50		I	but they'll all be the same
51		K	mm mm 'cos it's the same thread that goes through the brazeons
52		I	and ther's plenty of room for it
			so 'cos we have access to the outside here
53		J	yeah maybe I mean I I wouldn't feel horrible if we gave away the er idea of locking it but ur
54		I	well we'll just throw in an extra set screws
			so people who want it can do that [K:mm mm]
55		J	the set screw or maybe there's a way em if you're gonna lock your bike
56		K	just do it as an allan wrench
57		J	there's a way to lock through through it
			there's some like locking hole feature
58		J	for your [I: right] bike cable to go through
59		I	right just glue a little piece of aircraft cable on it[K: mm mm]
60		J	and a little padlock on the draw string [I: OK so K: yeah]
61	C	J	so let's get some dimensions on this turkey
	C		and er detail drawing phase
	C	J	do we know what this feature looks like
			it's just another lug feature right
62		K	mm mm our tray is pretty wide [J: let's come up with some]

Arguments - Delft individual protocol, segment 19

Argument modality: Figure (N=31, of which 20 at haed of move)
Argument modality: Rationale (N=6, of which 4 at haed of move)
Argument modality: Figure/Rationale (N=3, of which 2 at head of move)
C Argument modality: Comment (N=32, of which 16 at head of move)
No decisive modality (N=1, of which 0 at head of move)
Not an argument (N=1, of which 0 at head of move)
M=Move; Ar=Argument

M	Ar	Protocol
1		Ok em and in fact em I had another thought and that is to take advantage of that em
		[cont'd] space between guide to em er to em the em er this lug and the em brake
2	C	let me just check one more thing here
	C	oh no there is something funny about this thing see em
3	C	alright am I to ass- am I to assume that you don't have any additional
		oh I see what this is wait a second em
3	C	alright am I to ass- am I to assume that you don't have any additional
		oh I see what this is wait a second em
	C	am I I to assume that you don't have any additional em technical detail about this or
		[cont'd] can answer questions about that? [X: no, no]
4	C	OK so I've been given this the guys have gone home and I'm stuck with that
	C	OK it's five-ten I've gotta start getting to a more concrete design em
5		alright I'm assuming that that happens to be the brake guide em
	C	this little bushing in washer in in here em is not on the design em
6		that I'm going to assume is the brake
		no is is is the em fender mount
		because fenders mount like that sometimes I've seen them
7		rather than these two things being the fender
		I mean I've these two little bushings here I don't know what they are em er
	C	and you can't tell me what they are right these two little bushings?
	C	what what what what use are those little bushings? [X: they are mounting points
		[cont'd] for rear carriers]
8		they are mounting pooints for rear carriers?[X: yep]
9		good alright so it is a mounting point for a rear carrier em er and I wanted
	C	OK fine so em I just confirmed that
10	C	now you see you'd never know by looking at this design that that's a mounting point
		[cont'd] for a rear carrier
	C	but I guess em that's a nice thing to know
11		OK so I might have to change the approach a little bit here and say
12		alright we'll take advantage of that em
13		that is a er device that uses a em pin through there two pins em er
	C	OK em my thing is going to be er em

14	C	OK em right so we're going to have to scrap this scrap that this OK em
15	C	alright so we've learned now let's go on I think we'll just go on to another sheet so that
		[cont'd] the video can do better em
	C	I'm one who's messy and not that organized plus I don't draw very well so em
	C	we are em I'll just start a clean sheet
16		OK so we have that em rear thing coming down
17		we have those mounting holes for rear carriers
18	C	OK em that's in this perspective view em in the side view
	C	the perspective view doesn't show anything in detail enough em and so em I can see that
19		so we have this little pin here
		we have another er pin here
20		let me just see which is er it's got a hole through it
		the hole look[s] to me like they are
	C	this is a half scale em
		let's just take a quick look at this this thing here happens to be an eighth-inch pin
		[cont'd] eighth-inch pin
21		OK that's em er OK so that's an eighth yeah that's an eighth-inch pin em eighth-inch hole er
		that's not very big but em it might be all that's necessary em er
22		I'm going to make another assumption that these two don't line up em er em er er
23	C	well let's see em are you my technical resource? [X: am I?]
24	C	yes just out of curiosity are these two two em mounts here em mounted such that the
		[cont'd] em that the holes are in line? [X: they are in line]
25	C	they're in line [X: yeah]
26		and so an eighth-inch so a pin
27		and can you tell me what the diameter is is it an eighth-inch or is a as dimensioned off that
		[cont'd] [X: it's an eighth-inch]
28		alright its an eighth-inch and they're in line
	C	OK in line alright alright em
29	C	now in line is something that I never believe fully and not only that em
30		if you got into your first little bike accident and you ever bent this frame
		you might very well not have them in line
31		so to em er so I would be wary of trying to have a wire go through that
		and have something that gets removed and installed em on a regular basis
32		but to plug into one in each side that's fine em
33		I am assuming that these things are em brazed-on and em em and em
34		OK so let's just assume they're brazed-on
	C	now er brazing is not the greatest
	C	they don't look like they're really mounted very very well er
35		let me just check this thing that's a half inch em
		oh that's more than a half inch diameter
36	C	I'll just go through this thing again
		so so er three-sixteenths
		so there's three-eighth diameter oh three-eighth diameter well

37	C	OK so that might not be too bad
		I would say that the braze is probably er good enough and em
38		I'm also going to make an assumption that er Batavus em OK they wanna retrofit this
		[cont'd] thing em er em
39	C	well we'll just assume that that's strong enough em
40	C	I can calculate that and I'll do that later em check braze
41	C	OK and I will ask if if that is a braze
		by the way are these fittings brazed-on is that are they are they they brazed-on?
		or are they welded on? [X: they are brazed yeah]
42		brazed huh OK

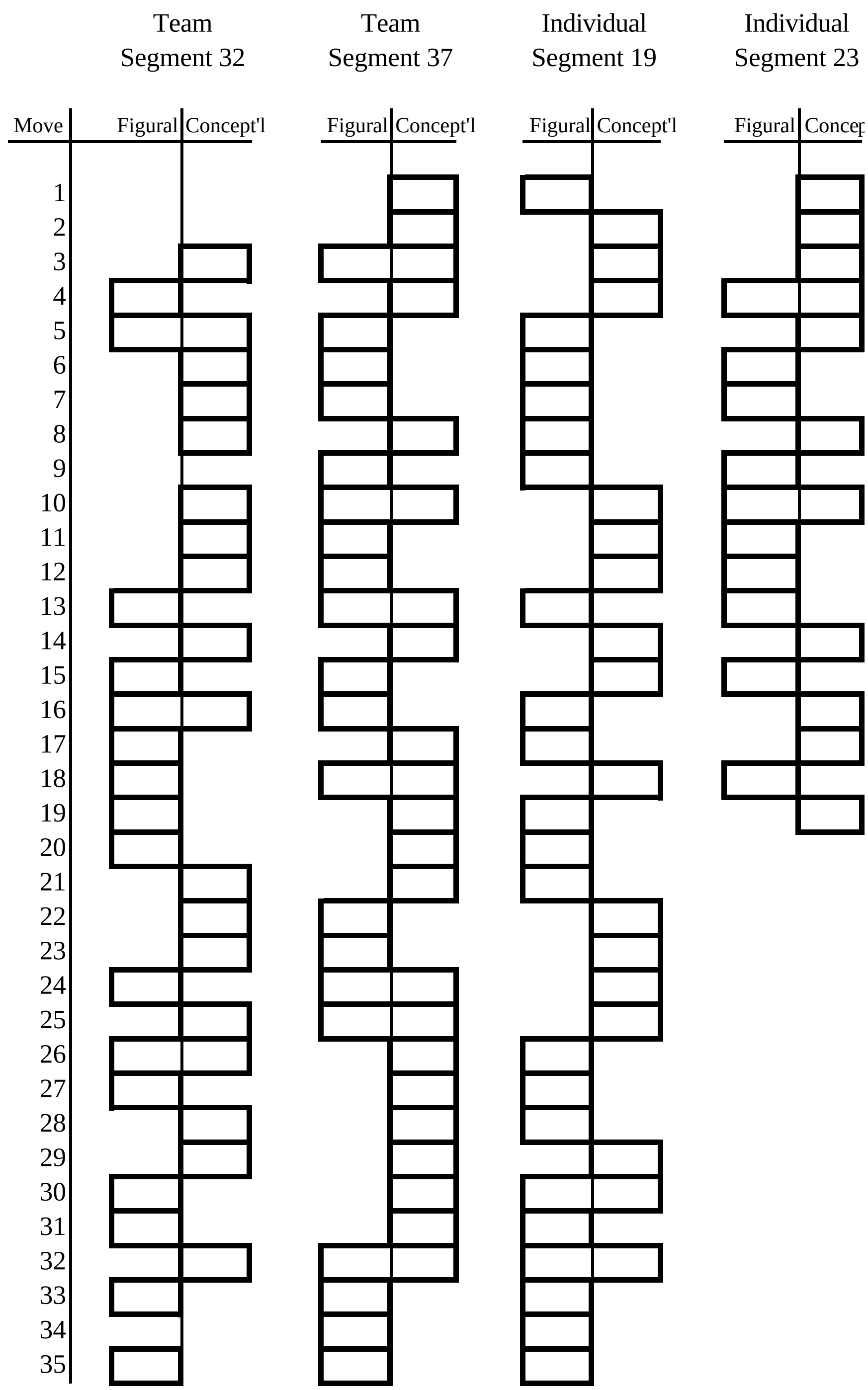
Arguments - Delft individual protocol, segment 23

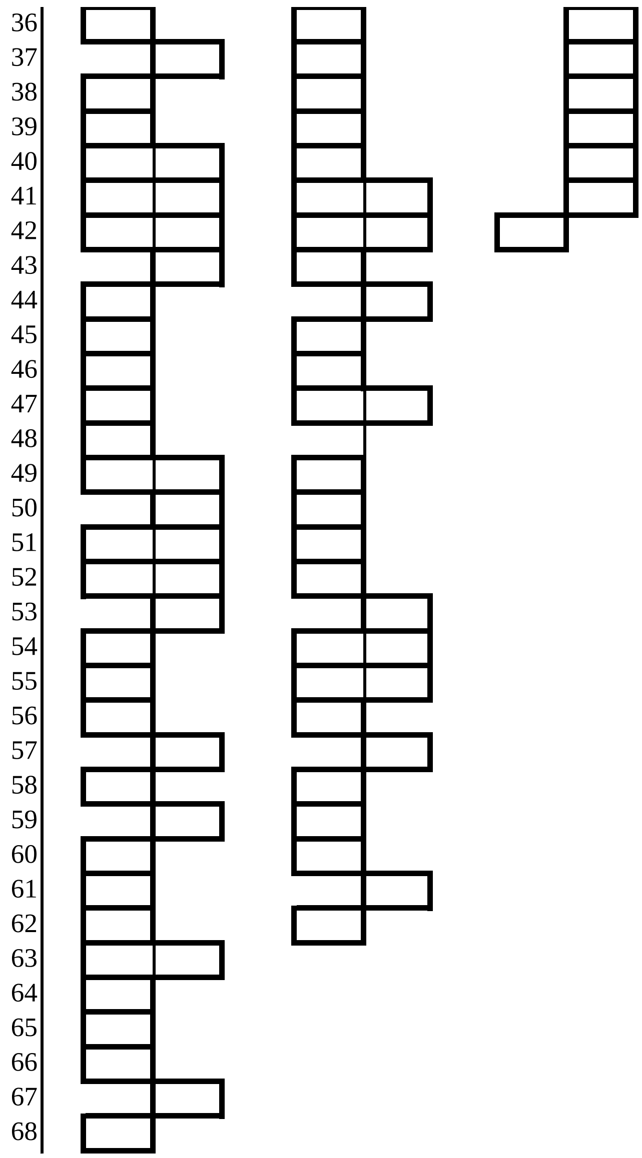
Argument modality: Figure (N=15, of which 8 at head of move)
Argument modality: Rationale (N=8, of which 6 at head of move)
Argument modality: Figure/Rationale (N=3, of which 2 at head of move)
C Argument modality: Comment (N=6, of which 3 at head of move)
No decisive modality (N=0, of which 0 at head of move)
Not an argument (N=2, of which 0 at head of move)
M=Move; Ar=Argument

M	Ar	Protocol
1		OK so it says it will fit on any bike
	C	so I was a little bit wrong but em er
		OK em OK em alright so em I think that em
2	C	alright so what we've got is em I think that this detail here
	C	cos it says any bike is what they want em er er er
3		OK alright so we want something that's really clearly related to this backpack directly
4		OK which would mean that we want the backpack to snap into it
5		OK first thing is that to make it a proprietary product for the Batavus backpack
		this er this this this this frame here will have U-channels on it
6		OK mounted on it unfortunately
7		alright we're gonna make it out of er like a steel tube
		or an aluminium tube
		with a U-channel on it and em
8	C	no we don't even need that
		what we're gonna have is we're gonna just have frames
9		gonna have a frame here end view
		and there's gonna be a er plastic em clamp clip alright
		which the backpack will snap into
10		now why would the snapped backpack stay in there snap snapped into the thing em
		when you might have large vertical loads
11		so we have one we have two times we want to have maybe four support points here
12		alright unfortunately we might only have er one
	C	let's just look and see this thing here em
13		alright so em it looks to me like er you could actually have one two three four
14		my weight estimate to er no more than fifteen punds in a pack like this
		so em and as a result I'm going to em er yeah
15		OK so alright so we're gonna have some little little plastic clips here on the back
		which the backpack will slip into
16		and em er that is going to be the feature the feature
17	C	another feature the feature em we need a feature
18		OK so what we got is we got a feature of the clips
		holding the backpack on

19
why do we want clips
because we want to take advantage of the fact that we're using an external frame backpack
internal frame can't use clips

Apendix 2. Grouping Types at Heads of Moves

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