The designer as a team of one

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Who does better in design, loners or teams? Different traditions, different tastes and different beliefs are in disagreement on this question. Theories that deal with this subject, to the extent that they exist, are based mostly on ad hoc *observations. In this study the productivity of the design processes of an individual and a team, who reach equally satisfactory results working on the same preliminary design task, are compared. A quantitative assessment system of parameters of design productivity is introduced and applied to protocols of the two processes. Detailed analysis leads to the conclusion that there are almost no differences between the individual and the team in the way they bring their work to fruition.*

Keywords: protocol analysis, creativity, critical moves, teamwork, productivity

Ever since Vitruvius' first century treatise on architecture, we accept axiomatically that a designer must know a little bit about everything because design work requires varied knowledge and an outstanding capability for mental integration and synthesis. What was always taken to be indisputable for architects, is also deemed true for other kinds of designers, albeit to a lesser degree. The ancient designer was an absolute authority who could handle any professional design challenge. The habit, or norm of team work in design, is a relatively recent phenomenon, emanating from the scope and complexity of many design tasks and the need for multiple expertise and division of labour. Team design is an appealing idea and in many settings we would not consider a different work routine today, supposing that as brilliant as it might be, Vitruvius' creed is no longer appropriate. However, there is little research to support the claim that team work in design is superior to that of an individual designer, and if so, in what way and under what circumstances. We approach this question from the perspective of cognitive science and ask: can we access the processes of design thinking so as to be able to compare the behaviour and performance of the individual to

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that of a team? We believe that we do have germane tools with which to study design thinking and we propose to do so in this study. We define the parameters of comparison between a team and an individual, and we present a methodology, based on protocol analysis, that we deem appropriate for the task. We show that from a cognitive perspective not much has changed since the days of Vitruvius, whose acute and insightful observation of designing appears to still be of interest.

1 Individual and team problem solving

In the engineering-oriented design professions it is common practice to initiate work on a new task with a collective ideation session, or brain storming. The task is assigned to a team and the team members are thus jointly involved from the very early stages of conceptual design. This is not the case in the more art-oriented design fields, where an individual designer is often responsible for the conceptual design phase. He or she may consult with colleagues and peers, but the responsibility is personal and a team steps into the picture at a later stage, with the chief designer's initial sketches given as a *fait accompli*.

It is therefore not surprising that there are design situations in which it is not clear which mode of practice is desirable for the front edge of the design process: a team effort or an individual's endeavour? Is the contribution of several minds to the conceptual phase an asset in terms of the breadth of issues that can be expected to surface and the number of alternative candidate solutions that may be proposed? Or does teamwork contribute, conversely, to a diluting of conflicting views because of pressures towards conformity and compromise? Is the single mind less constrained because it is free to explore unpopular directions or is it constrained by personal biases and limited expertise?

1.1 The problem

The above questions are not unique to design, and have been asked in the context of research on problem solving and on scientific investigation. Team work is generally considered more fruitful, at least potentially, and there is evidence that in scientific research collaborative work is constantly on the rise. In psychological research, for example, the mean number of authors per published article rose from 1.5 to 2.2 between 1949 and 1979[1]. This does not mean, however, that we have evidence that collaborative undertakings result in more satisfactory work. Kraut *et al.*[2] have shown that psychologists opt for joint research and authorship of articles despite lower satisfaction from the quality of such work, as compared to work they carry out and publish on their own. The reasons for seeking collaboration are therefore independent of the results and have to do with

1 **Over, R** 'Collaborative research and publication in psychology' *American Psychologist*, Vol 37 (1989) 996–1001

2 **Kraut, R E, Egido, C and Galegher, J** 'Patterns of contact and communication in scientific research collaborations' in **J Galegher, R E Kraut and C Egido (eds)** *Intellectual teamwork* Lawrence Erlbaum Associates, Hillsdale, NJ (1990) 149–172

social and personal dimensions that we shall not venture into here. Likewise, group problem solving processes in engineering are not necessarily superior to individual efforts[3]. Detailed studies show that the motivation of team members tends to decrease by as much as 30% where there is no personal penalty for slacking or no reward for successful performance[4]. Intergroup competition eliminates loss of productivity, but personal pay-offs are still essential. Good management can take this into consideration by designing compensation for group performance, as is habitual in sports, for example, where important victories lead to individual bonus payments to members of a winning team.

Given the above evidence, a comparison between individuals and teams in design, and particularly at the front edge of design, seems rather relevant. Industrial design protocols of a team and an individual at work on the design of a bicycle carrier is a particularly good opportunity for such a comparison for several reasons: a) industrial design lies somewhere in between engineering and the more artistically oriented design disciplines; b) protocol analysis is well suited for the comparison of processes that we are interested in; c) the equal settings of the two design sessions in question provide a considerable methodological advantage. One rarely achieves so much control over so many parameters of a design situation that is very close to real world circumstances. We would like to very briefly sketch a profile of our designers, the individual and the team, who arrive at relatively complete and satisfactory design proposals in the two hours allotted to the design exercise.

1.2 Solo design: Dan

Dan is an experienced mechanical engineer, who looks at the design of the bicycle rack almost exclusively from a functional point of view. He produces five sheets of sketches, the first of which appears only 45 minutes into the exercise. The considerable portion of time before he starts sketching (close to 40% of the total time) is spent studying the problem and getting himself informed about it. This is an intentional and typical strategy, he tells us, and declares: 'there's no sense in starting from scratch if you can start at square two instead of square one or square zero'. His exploration leads him to decide on a tubular design for his rack, and this decision is never questioned nor rated against alternative options. He takes a long time to decide on the location of the rack – front or rear of the bike, side mounted or symmetrically placed. Having decided on a tubular design and a central rear position for the rack, he spends most of the design time on joints between the rack and the bicycle. Connecting the given backpack to the rack is a secondary issue in terms of the time he spends dealing with it, and he finds a rapid solution to it which he refers to

3 **Lewis, A C, Sadosky, T L and Connoly, T** 'The effectiveness of group brainstorming in engineering problem solving' *IEEE Transactions on Engineering Management* Vol 119 (EM–22) (1975) 124

4 **Erev, I, Bornstein, G and Galili, R** 'Constructive intergroup competition as a solution to the free rider problem: A field experiment' *Journal of Experimental Social Psychology* Vol 29 (1993) 463–478

as a major feature of the design: plastic clamp-clips that are fitted onto the rack and into which the external frame of the backpack is snapped. Interestingly, decisions about the rack and its joinery to the bike and decisions on the backpack's joinery with the rack, appear to be derived from very different categories of design criteria: the former are based on a study of existing products and the conviction that bicycle manufacturers are good with tube handling. The latter is based on the wish to arrive at a 'proprietary product' because 'we need a feature'.

Dan's protocol was divided into 28 units by the subject matter they deal with, ranging in length from one to eight minutes, plus one unit that lasts 12 minutes. If we omit the longest unit in which he conducted a telephone conversation, we arrive at an average of four minutes per unit.

1.3 Team effort: Kerry, Ivan and John

The design team comprises three product design engineers who work together in practice. They have a moderate amount of experience – Kerry is somewhat more experienced than her colleagues. They work in a systematic manner that they seem to be practiced in and which requires little discussion among them on procedure. Fifteen minutes into the session they produce a timetable in which they divide their time into well-defined design phases and they ask Ivan to be their time keeper ('Mister Schedule'). They then enter a brain-storming phase in which they bring up issues and concepts and list them orderly on a whiteboard. They list the functional requirements, desired features and alternative options for the positions of the rack, concepts of joining the rack to the bike and the pack to the rack, and materials. The process is iterative and they discuss the different items on their lists several times. Human factors come up frequently, and a 'proprietary mounting thing' is rejected on moral grounds. The rack's position on the bike is determined easily at an early phase, and the work on joining the rack to the bike and that of connecting the pack to the rack receive about the same amount of attention. Many alternative solutions are explored, especially for the way the backpack can be attached to the rack. Special dual function features such as convertibility of the rack to a lock are considered, but abandoned later on. Questions of appearance come up, and the team looks for 'cool' ideas. They produce four sheets of drawings, of which only two contain actual design sketches, mostly three-dimensional, starting approximately half an hour into the process. In the last minutes of the session the team calculates manufacturing costs and arrives at a fairly complete preliminary specification for the designed product.

Although no division of labour is planned, apart from Ivan's role of time keeper (which he performs flawlessly), a careful analysis can point to group dynamics that produces social roles in the team, and it appears that each member contributes different dimensions to the joint effort. We shall have more to say about this in Section 5.2.

The team protocol was divided into 45 units by subject matter, ranging in length from one to nine minutes, and averaging 2.66 minutes per unit.

The question we must address next is that of criteria for a proposed comparison between the design team and the individual designer. We opt for productivity as the yardstick for commentary and analysis. But before we plunge into our study of productivity, we need to be absolutely sure that our two protocols are of a kind and that our protocol analysis methodology can be applied to them on equal grounds.

2 *Design thinking and verbalization*

The arguments for accepting reports of think-aloud exercises as a reflection of cognitive activity are well documented and substantiated[5] and require no further discussion here. But since our data consist of one think-aloud protocol and one protocol of a conversation, a question may arise regarding the compatibility of these two modes of thought verbalization. Can thinking aloud and conversing with others be seen as similar reflections of cognitive processes of the kind we want to investigate? We answer in the positive, adopting a Vygotskian view on the relation between thought and speech[6]. Vygotsky distinguishes between two planes of speech: the inner and the external. Inner speech is not a prelinguistic form of reasoning but the semantic aspect of speech, abbreviated speech, in that it centres on predication and tends to omit the subject of a sentence and words connected to it. Inner speech is a function in itself, not an aspect of external speech, but inner and external speech together form a unity of speech. Thinking aloud can be seen as being close to inner speech, whereas a conversation is certainly a sample of external speech. This is applicable to our case even though in our team protocol conversation takes place among team members who, through close association with one another and with their subject matter, achieve a fluency that is marked by numerous short cuts. Both the inner and external planes of speech are, however, more than representations of thought. To put it in Vygotsky's words: 'Thought is not merely expressed in words; it comes into existence through them.'[6] (p 218). We therefore accept our two protocols as equal windows into the cognitive processes involved in design thinking. We can now proceed to discuss design productivity, in terms of the design process, and will later present an analytic system with which we

5 **Ericsson, K A and Simon, H A** *Protocol analysis: Verbal reports as data* MIT Press, Cambridge, MA (1984/1993)
6 **Vygotsky, L** *Thought and language* MIT Press, Cambridge, MA (1986)

propose to examine the productivity of the design processes at hand, so as to be able to compare them.

3 Design productivity

The term productivity brings to mind issues of cost effectiveness and profitability. But it is also related to performance, motivation, efficiency, effectiveness, production, competitiveness, quality etc. We accept Pritchard and Watson's notion that the important issues to look at are efficiency and effectiveness[7]. We also accept their view that it is not easy to measure group productivity: interdependence among group members is necessary to achieve the group's goals. The patterns of such interdependence may be rather complex, and therefore the productivity of a group is not a simple sum of the performance of its members.

This leaves us with the need to find ways to assess effectiveness and efficiency in design thinking, as carried out by both individuals and teams. Efficiency is relevant to design thinking because it bears on creativity and expertise, among other things. Economy of thought, or the amount of mental resources that must be invested to obtain innovative ideas, is directly related to creativity[8]. Expertise has an even closer association with efficiency, because we know that the ability to take short cuts and thereby reduce the amount of labour that is required to arrive at satisfactory solutions to problems, is a hallmark of expertise. Creativity will figure in our discussion of the protocols, but expertise is not an issue we comment on here, since we are not comparing experienced and inexperienced designers in the present study. Effectiveness, which we shall more or less equate with productivity, will be our major concern.

Designing is a mode of thinking and our sense of the meaning of productive designing is akin to Wertheimer's sense of productive thinking[9]. For Wertheimer thinking is productive when it gives rise to genuine ideas, when it brings about the transition from a blind attitude to understanding, when one comes up with creative ideas, however modest the scope or the issue. It stands in contrast with rote thinking and with the following of a prescribed course of action. Productive designing, like productive thinking, is insightful and inquisitive and it is indispensable in problem solving when the problems are new and unfamiliar to the problem solver. Design problems are almost always new to some degree, and we therefore think of them as belonging to the category of ill-structured problems[10], that require productive processes to be adequately solved. We can easily assess design products: our problem is to correlate the quality of a product with the process that brought it into being. We need an analytic system that can dissect the design process so as to

7 **Pritchard, R D and Watson, M D** 'Understanding and measuring group productivity' in **S Worchel, W Wood and J A Simpson (eds)** *Group processes and productivity* Sage Publications, Newbury Park, CA (1992) 251–275
8 **Perkins, D N** *The mind's best work* Harvard University Press, Cambridge, MA (1981)
9 **Wertheimer, M** *Productive thinking* Harper Torchbooks, New York (1945/1971)
10 **Goel V** *Sketches of thought* MIT Press, Cambridge, MA (1995)

understand what cognitive mechanisms lead to productivity. The system that we propose is presented in Section 4.

4 Critical design moves

Our analysis of the design protocol is structural; it is aimed at facilitating access to cognitive aspects of the design process, particularly those related to productivity. We parse the protocol into design *moves*, and look at the design process in terms of relationships created by the *links* among moves. The system that was developed to notate moves and the links among them, *linkography*, is instrumental in comprehending structural patterns of design reasoning. We are unable to present the system in this abridged version of the study, and for a broader discussion the reader is referred to Goldschmidt[11,12]. We shall only explain the concept of critical design moves which is essential to the discussion that follows.

The meaning of 'move' in designing is akin to its meaning in chess: a design move is a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move. Moves are normally small steps, and it is not always easy to delimit a move in the think-aloud protocol of a single designer. In the present experiment, we define a move in Dan's protocol by establishing the beginnings and endings of coherent utterances. The team's protocol is easier to parse, and each utterance by one of the designers is defined as one move. Within each unit of the design process, the moves are numbered chronologically, as in the example below, which records four sequential moves from unit 32 in the team's protocol

17 OK bungees
18 compression straps that also snap
19 that's bun- that's bungee like
20 straps with snaps

For each move we pose but one question: is it linked to every one of the moves that precede it in a given sequence of moves such as a design unit? We use a binary reply system of 'yes' and 'no' only, and the sole criterion used to determine linkage or its absence is common sense, in the context of the design task. Thus we establish links among a given move and previous moves, and these links are called *backlinks*, because they go back in time. With hindsight, linkography allows us to specify the links that a move makes to subsequent moves. These links are the move's *forelinks*, because they go forward in time. In contrast to backlinks, which can be determined at the time a move is made, forelinks can be determined only after the fact, when the entire process is completed, and

11 **Goldschmidt, G** 'Linkography: Assessing design productivity' in **R Trappl (ed)** *Cybernetics and systems '90* World Scientific, Singapore (1990) 291–298
12 **Goldschmidt, G** 'Criteria for design evaluation: A process oriented paradigm' in **Y E Kalay (ed)** *Evaluating and predicting design performance* John Wiley, Chichester, UK (1992) 67–79

as a consequence of having registered all backlinks. The two kinds of links are very different conceptually: backlinks record the path that led to a move's generation, while forelinks bear evidence to its contribution to the production of further moves.

The number of links relative to the number of moves in a given sequence is an indicator of the 'strength' of the design process, or of its productivity. We contend that an effective design process is characterized by a high ratio of interlinking among its moves. The proportion of links/moves is termed the Link Index (LI); a correlation between high LI values and productivity has been established in our previous studies[11,12]. Individual moves, however, differ greatly in the number of links they form, both backwards and forwards. If a high number of links is indicative of productivity, then we should pay special attention to moves that are particularly rich in links, in one direction or the other (and rarely, in both directions). Link-intensive moves are called Critical Moves (CM), and all the Critical Moves of a sequence together describe its *critical path*. We maintain that like the Link Index, a quantified critical path serves as a good, in fact the best, indicator of productivity. We therefore count the CMs in each design unit and notate their percentage (out of the moves made in that unit). If the Critical Move is rich in forelinks, it is notated CM> and if it is rich in backlinks, its notation is <CM. A Critical Move that is rich in links in both directions is notated <CM> (in the present analysis there are only two such moves, one in the team's protocol and one in Dan's). CM> tend to occur early in a unit and <CM late in the unit, but we note that there are exceptions to this rational distribution. <CM> occur only at overlaps between chunks. In a quantitative study, we must determine how many links qualify a move to the status of a Critical Move. The number of links we choose for this purpose is arbitary, and depends on the grain of the analysis and on the purpose of the study. In the present study we refer to a move as critical if it generates seven links or more in one direction. The notation is CM^7 if the direction is of no interest, and $<CM^7$ or $CM^7>$ if we also relate the direction of the links. In a few cases we also inspect Critical Moves with six links, or CM^6.

We chose seven links to define the criticality of moves in this study for several reasons. First, the grain of analysis was quite dense, by which we mean that we were liberal in determining, by common sense, the existence of a link between moves. At this grain a lower number of links would have produced a very long critical path for each unit, veiling the structural information we can read off it. In an ideally structured process, a suggestive move is productive if it is followed by a series of moves that explore issue(s) raised by that initial move or related subjects. The

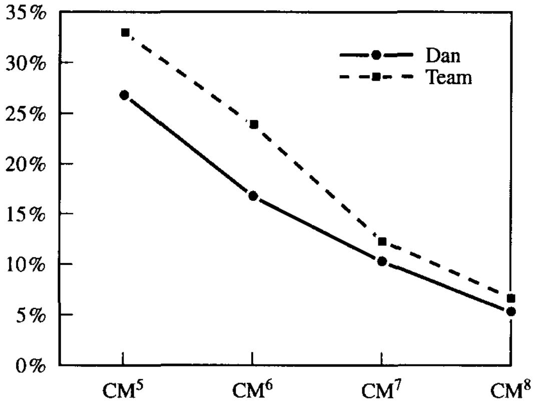

Figure 1 Dan and the team, %CM of total moves, by link level

exploration in turn is worthwhile if it leads to a concluding move, that summarizes or evaluates points raised in the exploration. The initial move will then be a CM>, and the concluding move will be a <CM. In highly structured processes we see this quite clearly, provided our Critical Moves are not too loosely defined. We found that at the level of seven links, we obtain the clearest structural representation. The second reason for choosing the level of seven links is speculative: we hypothesize that the number of previous moves one can link to, has to do with what we remember of what had been processed shortly before we make a new move. If we accept Miller's famous theorem[13] that we can hold up to seven (plus or minus a few) items in short-term memory, then this is the optimal number of links we can expect a link-intensive move to generate (in a few rare cases we find over ten links, but some of them can be interpreted as plain repetition). The last and most important reason for choosing seven links as the criterion for criticality is empirically defined. We constructed critical paths for the two protocols at the levels of five, six, seven and eight links per CM. The lower the number of links, the higher the %CM. Figure 1 shows the relationship between CM percentage in the 'move population' and the level of links defining them, for Dan and for the team.

We see that the two curves almost converge at level 7, whereas at levels 5 and 6 the difference between them is too large to allow a comparison between the two processes on the basis of Critical Moves. At level 7 the difference between the two is statistically no longer significant, as we shall see in the analysis presented in Section 5. We can therefore be sure that at level 7 there is enough of a common denominator that allows us to compare the two processes in terms of their productivity.

13 **Miller, G A** 'The magical number seven, plus or minus two: Some limits on our capacity for processing information' *Psychological Review* Vol 63 (1956) 81–97

We are now ready to engage in a detailed analysis of the bicycle design processes, on the basis of a Linkographic analysis. We hope to show that despite methodological difficulties, quantitative protocol analysis is a powerful tool in the service of design thinking research. We agree with Lloyd and Scott[14] that qualitative analysis is useful and can lead to important insights, but we propose that it cannot replace quantitative analysis which is equally insightful when based on sound theoretical grounds.

5 *Productive designers: Dan and the team*

A comparison between the two processes, by Dan and by the team, is no easy matter. The variables that we put to the test are structural, but they are influenced by content: the actual subject matter that the designer deals with at a particular point in the process has an effect on the kinds of moves he or she generates and how extensively linked they are to one another. We are unable to process the protocols in their entirety and must therefore try to select portions from the protocols that are reasonably compatible. Compatibility is judged by content, or subject matters that are as close as possible to one another. We were interested in hard-core design activity, i.e. a stage of neither information collecting or clarification, nor summaries or calculations. We believe we found matching portions: for the team, they are units 32–37, where unit 34, which lasts only one minute, is not treated separately but is combined with unit 35. The entire sequence lasts 21 min, from 1:17 to 1:38 h into the process. From Dan's protocol we selected a 25 min sequence, from unit 19 to unit 23, beginning at 1:29 and ending at 1:54 h into the process (note that the team's actual work starts at 0:05 h and Dan starts at 0:17 h. For ease of reference the time indications are given as stamped in the protocol, but if we measure time from the moment in which work starts, we obtain 1:13 h for both Dan and the team!). The two selections deal with subject matters that are as close as we could have hoped for, but the order in which these subject matters are taken up varies. Table 1 lists the selected units and shows the subject matter categories into which they were paired (to be discussed in Section 5.1). It also summarizes the number of moves, links, CM^7 and $CM^7>$ that were found in these units in the process of linkographing them.

If we calculate the mean Link Indexes for these portions, we find that the team LI =2.75, and for Dan LI=2.67. The difference is not significant ($p \geq 0.6$). The CM^7 percentage of the total number of moves is 12.42% for the team, and 10.14% for Dan. This difference is also not significant ($p \geq 0.1$). (see also Figure 1). The similarity between the LI and CM^7 values of Dan and the team are particularly interesting because of the striking difference in the absolute number of moves, links and Critical

14 **Lloyd, P and Scott, P** 'Discovering the design problem' *Design Studies* Vol 15 No 2 (1994) 125–140

Table 1 Comparable units for analysis

Dan

Unit No.	*Catg.**	*Subject matter*	*Min's*	*Moves*	*Links*	*CM⁷*	*CM⁷>*
20	A	Revised tubular design	5	31	63	–	–
23	B	Feature: clamp-clips	4	19	72	6	4
22	C	Snap-on plastic plate	4	22	58	3	1
19	D	Mounting points (braze-ons)	8	42	112	3	2
21	E	Bottom joint	4	24	53	2	1
		Total	25	138	358	14	8

Team

Unit no.	*Catg.**	*Subject matter*	*Min's*	*Moves*	*Links*	*CM⁷*	*CM⁷>*
37	A	Complete rack and joints	5	62	165	5	4
32	B	Tray and fastening devices	4	68	203	13	8
33	C	Tray features	1	16	36	1	1
34/5	D	Mounting (hum. factors) and mounting points	6	78	227	12	7
36	E	Features of (braze-on) joining	5	74	216	6	1
		Total	21	298	847	37	21

*Categories: A, overview revision; B, major features; C, feature alternative/assessment; D, essential checks (mounting points); E, particular details (bottom joint)

Moves that are made by Dan and by the team. Dan is slower, he takes much longer to respond to his own moves than the team members take to react to one another. Does this imply blessed thoughtfulness, that can be assumed to contribute to the linkability of moves? Our results do not suggest that this is the case. At the same time, the results do not support an assumption that the fast ping-ponging of ideas among team members necessarily generates a more cohesive body of interlinked moves than that of the slower individual designer. The similar values we obtain for the two variables under scrutiny, lead us to the preliminary conclusion that both processes are basically equally productive.

This is an important conclusion, that we wish to explore further. How are these productivity values achieved, and when are they at their peak? Conversely, what correlates with a decline in productivity? In particular, we would want to find out what difference, if any, can be attributed to the singleness of Dan versus the group dynamics in the team's work? Furthermore, is Dan really talking in a single voice, and can we point to differences among the individuals that compose the team? The rest of this section takes a look at these questions.

5.1 Design units and productivity correlates

The overall figures make it possible to draw a rough comparison between Dan and the team, but they teach us nothing about the reasons for design productivity. To gain some insight into what triggers fruitful designing, we must return to the units into which the processes were subdivided, and try to see what it is in them that can explain high or low values of LI and CM[7]. To do this, we shall first comment briefly on these units.

Category A: overview revision

Dan looks at his tubular design while also thinking about joints. He is not sure of his decisions and changes them often, reassuring himself that the tubes are a wise choice. The team makes its overview revision after having assessed partial solutions for several of the problems they have identified. They address the conflict that is raised by the need to fold the rack while also wanting to emulate the existing, nonfoldable Blackburn rack.

Category B: major features

This is where both Dan and the team make major breakthroughs. Dan decides on a proprietary product 'that clearly relates to this backpack directly'. The team comes up with the idea of making a tray that can contain the backpack's straps and prevent them from 'dragging in the spokes'.

Category C: feature alternative/assessment

In Dan's design, this unit precedes his 'feature' invention. He tries out, but does not develop, the idea of a vertical plastic plate over which the pack's frame would fit, thus holding it in place. The team makes a fast evaluation of the tray idea that has been suggested in the previous unit, but they sidetrack to other issues.

Category D: essential checks: mounting points

This is Dan's earliest unit in the sequence, in which he inspects possible mounting points, requests information, tries to understand the given drawings and discovers braze-ons. The team is interested in ease of use, which leads to an investigation of the advantages and disadvantages of mounting the rack to braze-ons.

Category E: particular details (bottom joint)

After his overview revision, Dan designs the bottom joint to the rear axle, led by the wish to provide a 'quick connect' solution. The team, having decided on braze-ons, designs the bottom joint. Their solution is basically similar to Dan's.

Table 2 Ascending sequence of LI and %CM^7 by category (underlining and dotted underlining indicates close and relatively close values, respectively)

Dan	LI	A (2.03)	E (2.21)	C (2.64)	D (2.67)	B (3.79)
	%CM^7	A (0)	D (7.14)	E (8.33)	C (13.64)	B (31.58)
Team	LI	C (2.25)	A (2.66)	D (2.91)	E (2.92)	B (2.99)
	%CM^7	C (6.25)	A (8.06)	E (8.11)	D (15.38)	B (19.12)

If we calculate LI values and CM^7 percentage values for each unit in the two processes and arrange them in an ascending order, we obtain the picture shown in Table 2. The table teaches us a number of things. First, there is a partial, but not full correlation, between the LI and %CM^7 values of the two processes. The sequences begin and end with the same categories, but the order differs somewhat in the interim units. This means that the critical path is not an automatic consequence of high interlinkability among moves. Secondly, the units of category B, in which both Dan and the team made breakthroughs in terms of introducing major features of their designs, have the highest values on all counts. The boost is particularly dramatic in Dan's case. At the other end of the gamut we find two different types of unproductive design phases. In Dan's case, it is mostly a stage in which he repeatedly questions his major decisions and puts them to the test. The team on the other hand, makes few moves in this phase before it sidetracks; the conversation goes nowhere and the team members realize that they must switch to a different subject matter in order to make progress. We learn a lot here about the cognitive nature of breakthroughs and what categorically prohibits them from happening. This point deserves a thorough investigation which is beyond the scope of this paper, but we shall add a few more remarks on this issue in Section 5.3. Thirdly, when comparing Table 2 with Table 1, we notice that there is no correlation between the chronological order of the units and the height of the LI and %CM^7 values reached in them (in Dan's case, the order is close to chronological). We must bear in mind that in both cases we selected portions from the midst of the protocols, with no clear-cut beginnings and endings. Still, we would like to propose that this finding suggests a nonhierarchical structure of the design process, at least in terms of its productivity. Likewise, there is no correlation between the values of our two variables and the lengths of the units. Fourthly, we notice that in Category E, in which Dan and the team engage in very similar searches (designing the bottom joint of the rack to the bicycle) and reach almost identical results, their %CM^7 are almost identical. This finding, too, may give rise to assumptions regarding cognitive apparatuses, but obviously

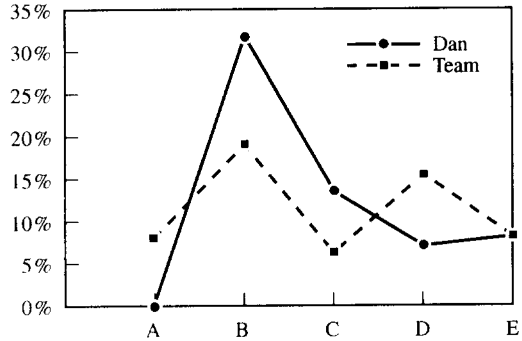

Figure 2 Dan and the team, %CM[7] of total moves, by category

more statistical data is necessary in order to propose a general hypothesis. Figure 2 shows the CM[7] percentage of Dan and the team relative to the categories.

Given the above analysis, we must conclude that at least for the portions we analysed, Dan and the team are equally productive. Not surprisingly, there are 'local' differences, which raise a question regarding the validity of the analysis sample. In other words, how can we know that the portions we dealt with are sufficiently representative of the entire process? Had we selected the units in categories A, D and E only, our results would have indicated that the team is more productive than Dan. If instead we would have selected only the units in categories E, C and B, the opposite trend would have emerged. We do not have an exhaustive answer to this question, and we find it hard to predict the results of the entire process, although we believe that the differences in productivity, if any, would be minimal. Statistically, our larger sample should give superior indications, and this is particularly the case because we have reached such a good match between the selected portions. Finally, we certainly do not claim that individuals and teams are always equally productive: they cannot be, just as two different teams or two individuals are not necessarily equally productive. What we do suggest is that the productive design behaviour of individuals and groups is defined by the same cognitive parameters, which can be observed and measured. The measured values of these parameters are similar for teams and individuals who reach equally productive results in the same design tasks.

5.2 *The team and its members*

Until now we have treated the team as a single entity. But we know that it is composed of three designers, and we would like to briefly explore their design behaviour profiles and their respective contribution to the team's work. A study in the framework of 'small groups' could throw light on a

Table 3 Team members' moves per unit by category

Designer	*Moves*	*A-37*	*B-32*	*C-33*	*D-34/5*	*E-36*	*Total*
	Moves	14	18	6	29	22	89
Kerry	CM^7	–	2	–	8	2	12
	CM^7>	–	1	–	5	–	6
	Moves	21	21	5	23	25	95
Ivan	CM^7	1	4	–	2	2	9
	CM^7>	1	3	–	1	1	6
	Moves	27	29	5	26	27	114
John	CM^7	4	7	1	2	2	16
	CM^7>	3	4	1	1	–	9

variety of issues such as leadership or other social roles[15,16], but such a study is beyond the scope of the present investigation. We therefore limit our brief commentary to the cognitive parameters that we have used so far in the analysis, whose values are given in Table 3.

The first thing we notice is that the three designers are not equally active and make a different number of moves throughout the selection. It is therefore not surprising that the number of Critical Moves that the three generate is not equal either. However, we note that the respective contribution of each designer is not directly proportionate to his/her level of activity. Figure 3 shows the contribution of CM^7 by the three designers relative to the total number of moves in each unit.

If we inspect the values closely, we notice that only Ivan's contribution follows roughly the general ascendance trends of the team as a whole, as given in the sequence in Table 2. John's contribution is equal or higher than that of his colleagues in all five units, and Kerry's share is equal or lower, with the exception of one unit in which she makes a very significant

15 **Hare, A P** *Creativity in small groups* Sage Publications, Beverly Hills, CA (1982)
16 **Hare, A P** *Groups, teams, and social interaction* Praeger, New York (1992)

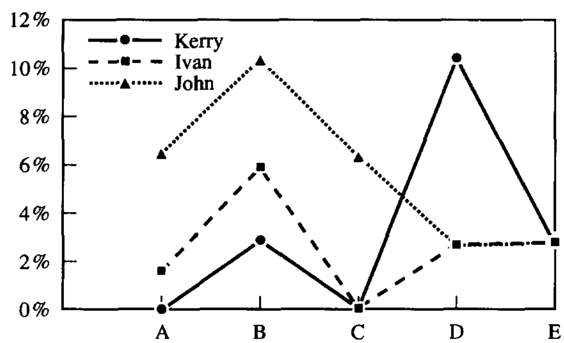

Figure 3 Team members, %CM^7 of total moves, by category

leap and generates a large number of critical moves. In this unit she is also much more involved than usual, generating over 37% of the moves. This is the unit in which mounting the rack to braze-ons is discussed and finally decided on. Of the three designers, Kerry is the most experienced bicycle rider and John states: 'we can assume Kerry has expert knowledge'. It is possible that the opportunity to make specific contributions when the circumstances call for it explains the sudden upward slant in Kerry's productivity curve, which is otherwise relatively low (at some point, when teased by her friends, she says jokingly: 'help, I want out of this design exercise', which may mean that she was experiencing a problem. If so, it may have impaired her performance). We do not know, of course, if sudden productive peaks are typical of her design behaviour, but in this sample it is a predominant trait.

These results must be reviewed with great caution because, we ought to remind ourselves, we are talking about interdependency among the team members. Neither Table 3 nor Figure 3 tell us anything about the preparatory moves that enabled team members to 'score' at the CM^7 level. If we check the results at the CM^6 level, for example, we obtain a different picture: out of 71 relevant moves, Kerry makes 20 (28.2%, as opposed to 32.4% at the CM^7 level), Ivan makes 25 (35.2%, versus 24.3%) and John makes 26 CM^6 (36.6%, versus 43.3%). We see that for the CM^6 level, results vary significantly from those obtained for the CM^7 level. To establish the contribution of team members to the design process, it is therefore not enough to look at partial 'bottom line' results, because interdependency within the team signifies that a particularly productive move by one designer may build on a preparatory move by another member of the team. The situation is analogous to that of a sports team, say a basketball team: the 'stars' who score most of the points cannot possibly do so without effective defense players and so on. To better understand the individuals' contribution to a team effort, we must return to the protocols for a qualitative analysis of the roles they assume. The limited scope of this study forces us to do so in a cursory manner, which does not replace an in-depth study, which we propose to undertake elsewhere.

John, as we already know, is the most active member of the team in this task. He is also the designer who comes up with the largest number of innovative ideas, some realistic and others less so. He is the one who first suggests the tray idea for the rack, which becomes the backbone of the design proposal. He convinces his friends, not without some discussion, to abandon the example of the existing Blackburn rack, which includes several metal tubes that together guarantee stiffness and strength. He argues in favour of a single 'beefy' tube instead, so that with the help of a pivot, the rack could become foldable, as required. He wants colour bungees and colour anodization of the aluminium tubes so as to achieve an attractive product, because to him: '. . . all design eventually comes down to a popularity contest'. He appears to see suggesting and cultivating new ideas (by himself and by others) as one of his major roles in the team.

Ivan is more conservative, and thinks more in terms of the precise givens of the task: 'not constraints but we'll call them caveats or whatever I dunno just possible we have to design around'. He finds it easy to accept other people's ideas and even when he disagrees, he is willing to consider them as options. In his role as time keeper he actually acts as project manager in this task, and takes it on himself not only to make sure that the schedule is followed, but also that each issue is comprehensively dealt with before it is time to move on. His involvement increases when detailed design is undertaken; he makes sure that solutions are robust and that all performance criteria are strictly met. On the whole, he appears to contribute primarily in the summation of ideas and decisions, in addition to managing the process.

Kerry is mostly concerned with the 'functional spec'. Many of her remarks pertain to functional matters and are marked by a 'no nonsense' attitude. She is in favour of an 'idiot proof [product], one way to install or one way to attach, and make it obvious too'. As noted earlier, she becomes very active when she can put particular expertise to use, in this case functionally oriented knowledge. At the same time she is also interested in 'a little bit of product identity'. The profile of her design behaviour in this task is less clear than that of her colleagues.

With a gross simplification, we could say that John pushes the team's work in a creative direction, Ivan makes sure that decisions are made only after proper assessment, and Kerry steps in when she feels she can contribute expert knowledge. Needless to say, none of the designers is one-dimensional and they all participate in a multitude of ways, but they each have their own thrust none the less. The question we must answer now is: how, if at all, can all of this be reflected in our quantitative productivity study? Is there anything in the givens that correlates with the qualitative profiles just presented? And is there a way to compare the team with Dan in this respect? To answer this question we turn to an observation that we have not utilized in the analysis so far: the division of Critical Moves into those with forelinks, or $\text{CM}^{7}>$, and those with backlinks, or $<\text{CM}^{7}$.

5.3 *Forelinking Critical Moves: the creativity component of productivity*

Critical Moves with backlinks may have various meanings, from evalua-

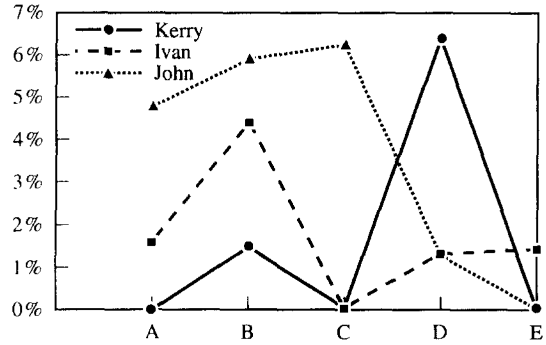

Figure 4 Team members, %CM[7]> of total moves, by category

tion to summary to plain repetition. Critical Moves with forelinks are usually suggestive in that further moves build on them. We therefore associated CM> with a measure of innovation, invention and, in the extreme, with creativity, even if at a limited and local scale. We thereby substantiate and quantify Gruber's assertion[17] (p 177–178) that 'interesting creative processes almost never result from single steps, but rather from concentrations and articulation of a complex set of interrelated moves'. This is relevant to our discussion because innovation, invention and creativity are undoubtedly contributing factors to productivity. We therefore wish to show that our findings regarding CM[7]> correlate with the qualitative profiles we drew from the protocols, in order to sustain our claim that productivity of processes can be observed and quantified up to this degree. We do not intend this to be a study of creativity, which is one of the most complex and multifaceted issues in cognitive science, and that deserves, in the context of design research, much more attention than we can possible devote to it here.

We want to look at CM[7]> at two levels. Within the team, we check the respective contribution its members make. Then we look at the team as a whole, and compare it to Dan's performance in terms of %CM[7]>. Figure 4 compares team members to one another, and Figure 5 compares the team with Dan.

Not surprisingly, Figure 4 shows that most of the time, John makes the highest percentage of CM[7]> (3.0% of the total number of moves), followed by Ivan and Kerry (2.0% each). Kerry's single outstandingly productive unit contains five out of the six forelinking critical moves she makes, and during the rest of the process Ivan scores higher than she does. As in the case of the total number of CM[7], here too it is wise to also look at the preparatory moves, and we turn to CM[6]>. We obtain different statistics: out of 41 relevant moves, Ivan makes 18 (43.9%, as opposed to

17 **Gruber, H E** 'Afterword' in **D H Feldman** *Beyond universals in cognitive development* Ablex Publishing Corp., Norwood, NJ (1980) 177–178

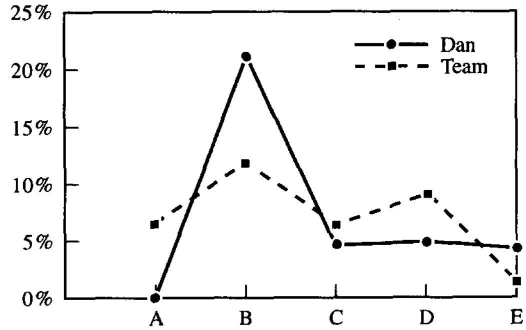

Figure 5 Dan and the team, %CM^7> of total moves, by category

28.6% at the CM^7 level), John makes 14 (34.2%, versus 42.8%) and Kerry makes 9 (21.9%, versus 28.6%). How do we interpret these results? We believe that they are congruent with the profiles we outlined above. John is the team member who comes up with the largest number of new ideas, but he also builds on the ideas of his teammates. For example, John says he likes Ivan's idea of attaching a net to his tray, and proceeds to take it further. Some innovative ideas remain undeveloped, others deal with small details that require little discussion; moves that contain such ideas are reacted to by fewer than seven forthcoming moves. This does not make them unimportant to the process or less creative necessarily. Still, CM^7> attract the largest number of responses, although they are certainly not all innovative or inventive, nor even necessarily the most innovative or inventive moves. They represent those ideas that played a decisive role in the design search, regardless of their inclusion in, or omission from, the final result. For example, when John says: 'so it's either a bag or maybe a little vacuum formed tray, kinda, for it [backpack] to sit in,' he makes a CM^7> that turns out to be decisive to the process. When Ivan says: 'or you can just – OK, so lockable knobs is one option, I think, if you want to take the rack off a lot or not; and then how about just er set screws or Allan head,' he expresses two alternative ideas, of which one only, the knobs, will remain with the design until its completion. Thus, in a greatly simplified manner, we may say that John brings many fruitful notions to the foreground of the process, making forelinking moves that prove to be critical all the way to the level of CM^7>. Ivan does the same with somewhat less grand ideas and therefore has a less impressive record at the CM^7> level, but is highly influential at the level of CM^6>. Kerry, who maintains a low profile but makes a concentrated effort to resolve the all-important question of mounting points, has a low CM> score at levels 6 and 7 alike, with a local high peak.

Figure 5 compares the combined team's creativity-bound Critical Moves with those of Dan. When comparing Figure 5 with Figure 2, we see that there is a strong similarity between the two: $\%CM^7$ in both processes relate to one another as do $\%CM^7>$, with small local differences. This is easy to understand when we calculate the percentage of $CM^7>$ out of CM^7 for both processes in their entirety: 56.8% of the team's CM^7 are forelinking, while for Dan the figure is 57.1%, an almost identical percentage. As we see, the distribution over design units is also quite similar for both $CM^7>$ and CM^7, which suggests a strong correlation between creativity and productivity.

6 *A team of one?*

The stable proportion of suggestive moves in the critical path, approximately one half, was corroborated in other studies of the design process[12], and appears to be independent of a variable such as LI. The fact that we do not reach higher values even in the most creative (or productive) portions of a design process, supports our claim that in an interactive and interdependent process even virtuoso, creative acts rely on evaluative, sometimes repetitious acts that define, constrain and clarify the problem space of the design task. When a team acts together, implicit or explicit roles are created for the team members, along disciplinary or behavioural lines. In this respect it is immaterial to the discussion whether or not division of labour is established in advance, along lines of expertise or other criteria. When the designer works on his/her own, with no teammates to collaborate with, it is still necessary to produce summative and evaluative moves along with the suggestive, creative ones, for a process to be productive. The single designer must therefore assume production of all types of moves, whereas in a team situation he/she could develop a permanent or an *ad hoc* 'expertise' in the production of a certain type of moves, or in a pattern of production that takes advantage of the strongest capabilities of all participants in order to advance toward the best possible results. We believe we have demonstrated that in Dan's process, we find precisely this behaviour. He oscillates between overviews and technical details, between functional aspects of the design product and issues related to human factors. He thinks of features, product identity and aesthetics along with stiffness, strength and ease of production. Team members do the same, but they can let a colleague answer a question they raise, or pick up someone else's line of thought and build on it. The single designer has only him/herself to rely on, and he/she must act as a team and give all the answers while also asking all the questions, often within the same move: 'why do we want clips? Because we want to take advantage of the fact that we're using an external frame backpack. [An] internal frame can't use clips'. Dan 1 asks, Dan 2 answers, Dan 3 gives the design rationale. One might ask whether the argument is not turned on its head: does the team not act as a single designer? We believe that Figures 3 and 4 and the related commentary suggest that this is not the case. If the team operated as an individual designer, what would the performance curves in Figures 3 and 4 correspond to in the single designer? We cannot answer this question and therefore we must assume that the team participants do not resemble different aspects of the individual designer, but rather that the individual designer is a unitary system that resembles the team.

We believe that among others, our findings may have implications for design education as well as for design management. At the least, we hope that these findings can be used to help establish a research agenda towards a possibility of such implications.

7 *Acknowedgments*

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