Risk Analysis, Vol. 23, No. 2, 2003

The Use of Mental Models in Chemical Risk Protection: Developing a Generic Workplace Methodology

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We adopted a comparative approach to evaluate and extend a *generic methodology* to analyze the different sets of beliefs held about chemical hazards in the workplace. Our study mapped existing knowledge structures about the risks associated with the use of perchloroethylene and rosin-based solder flux in differing workplaces. "Influence diagrams" were used to represent beliefs held by chemical experts; "user models" were developed from data elicited from open-ended interviews with the workplace users of the chemicals. The juxtaposition of expert and user understandings of chemical risks enabled us to identify knowledge gaps and misunderstandings and to reinforce appropriate sets of safety beliefs and behavior relevant to chemical risk communications. By designing safety information to be more relevant to the workplace context of users, we believe that employers and employees may gain improved knowledge about chemical hazards in the workplace, such that better chemical risk management, self-protection, and informed decision making develop over time.

KEY WORDS: Mental models; risk communication; chemical risks; drycleaning; soldering

1. INTRODUCTION

This article presents a theoretical and empirical framework for developing a methodology to formulate written risk communications about chemical hazards routinely found in the workplace, supported by the findings in a study involving small and medium-sized enterprises[2] (SMEs) in the United Kingdom.[(1)] Currently, workplace chemical safety information in Europe and North America is communicated primarily by means of Material Safety Data Sheets[3] (MSDSs) provided by the chemical manufacturer or supplier. However, the extensive detail and technical jargon contained in MSDSs appear to render much of the information inaccessible to many chemical users in the workplace. Furthermore, potentially useful safety information contained in MSDSs may be embedded in other less relevant information and, despite the detail, may lack use and protection information required by the workplace context. Making safety information more relevant to the workplace context of users should help employers and employees improve chemical risk management, self-protection, and informed decision making.

The research reported here uses the "mental models" approach in a comparative study of two chemical sectors, evaluating the possibility of creating a generic methodology for the design and evaluation of written risk communications. The approach builds on earlier work at Carnegie Mellon University (CMU)[(2–6)] and at Technische Universität Berlin.[(7)]

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2 Here defined as less than 50 employees.
3 Referred to in the United Kingdom as "Safety Data Sheets."

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Our objective was to deliver risk communications that were user-centerd in their content and form, focused on information relevant to users.[8–10] The intention throughout was:

1. To understand the target audiences' frames of reference for the risk communications;
2. To draw out some of the tacit beliefs and understandings about chemical risks on which workers may base decisions about the chemical risks in their workplace; and
3. To identify users' critical safety information requirements regarding chemical risk protection at work.

We adopted a new comparative approach, looking at different chemical sectors, in order to analyze the different sets of beliefs held about chemical hazards in the workplace. The study mapped existing belief structures regarding the risks associated with two chemicals in different workplaces: perchloroethylene solvent in the drycleaning business[11,12] and rosin-based solder flux in the electronics industries. "Influence diagrams" were used in the normal way to represent beliefs held by chemical experts, while "user models" were developed from data elicited from open-ended interviews with chemical users, adopting a qualitative approach not fully attempted in previous such studies. The juxtaposition of expert and user understandings of chemical risks enabled us to identify knowledge gaps and misunderstandings and to reinforce appropriate safety beliefs and behavior.

This article discusses how sensitivity to the impact of workplace culture on beliefs about chemical risks facilitates identifying user-relevant risk communication content. It concludes with a discussion of the efficacy of the methodology and suggestions as to how it may be taken forward.

2. APPLYING A "MENTAL MODELS" APPROACH IN CHEMICAL RISK COMMUNICATION DESIGN

The chemicals studied in the comparative design were perchloroethylene (perc) and rosin-based solder flux (solder flux), described further in Box 1 and Box 2, respectively. These two chemicals were selected to provide different hazards and workplace contexts. These differences were intended to improve the generality of the methodology.

Box 1. Perchloroethylene Use in Drycleaning

Perc is a volatile chlorinated solvent, widely used for garment cleaning in the drycleaning sector. In the United Kingdom, the sector comprises an estimated 6,500 units,[13] predominantly "high street" independents and small chains of businesses with a relatively high proportion of working owner/managers. Perc is heated within a fully enclosed mechanical system so as to mobilize dirt off the fabric of garments being washed in the perc. Temperature elevation promotes the vaporization of the perc, and mechanical process controls are utilized in an attempt to recover the vapor before it enters the workplace environment.

Box 2. Rosin-Based Solder Flux Use in the Electrical/Electronics Sector

Rosin-based solder flux is a naturally occurring resinous material variously applied during soldering activities in the electrical/electronic sector to improve the efficacy of the soldered joint. Flux comprises resinous acids that remove oxides and sulfides from the surfaces of components being soldered, and serves to reduce the surface tension of the heated solder alloy (normally a tin and lead mixture) and to inhibit the oxidation of component surfaces.[14] Flux may be used in liquid, paste, or jelly form, or may be supplied as part of the solder alloy itself, typically as cores imbedded within solder wire. The chemical sector is structurally diverse, comprising a range of SMEs from small self-employed TV repair shops undertaking periodic hand soldering, to high turn-over businesses manufacturing printed circuit boards in automated production lines maintained by skilled operatives.

We anticipated that the different organizational and social characteristics of the two sectors of industrial activity might affect how safety information is communicated, understood, and acted upon. For example, they could differ in the social organization of the work task or their wider "safety culture."[15–17]

Table I. Characteristics of the Two Selected Chemical Sectors in the United Kingdom

	Perchloroethylene Use in Drycleaning	Rosin-Based Solder Flux Use in Electrical/Electronics
Organizations	Homogeneity across the sector	Diversity in the sector
Proprietorship	Working owner/managers, and some chains of businesses	Companies and self-employed businesses
Workforce	Working owner/managers and employees; semi-skilled and unskilled; some manual work; absence of formal training	Self-employed and employees; skilled and semi-skilled; technical work; formal training may be required
Chemical identification	Recognized as a chemical by experts and users alike	Not always recognized as a chemical, and supplied in a variety of forms
Chemical hazard	Chemical itself is considered potentially "dangerous"	Chemical itself is not widely considered a risk to users
Chemical use	Workplace use and storage is considered hazardous and is controlled	The hazard arises from the process of using the chemical

Accordingly, user models were developed (Section 2.2) to capture some of the organizational complexity within these differing workplaces. Summaries of the characteristics for the two sectors discussed in this article are given in Table I.

2.1. Developing the Expert Influence Diagrams

The methodology for designing user-centered chemical risk communications in this study involves the *iterative* development of influence diagrams, supported by the evaluation of contextual data elicited in "user models." Atman *et al.* describe "influence diagrams" as directed networks.(2) We have used them to represent an inclusive expert understanding of factors (substances, equipment, working practices, people, and states of systems) and dependencies (relationships and interactions between factors) in workplaces and operational processes.

The influence diagrams for both selected chemicals are structured around five domains, illustrated in Fig. 1: chemical exposure, the means of control and prevention of exposure, and health effects potentially resulting from exposure. This generic framework developed out of the many discussions within the research team and our understanding of the literature in this field.(18,19)

Significantly, this theoretical framework can embrace wider considerations (e.g., the economic environment, workplace safety cultures) as well as aspects of expert uncertainty and points of expert disagreement (e.g., the carcinogenicity of perc). Our interviews found that such wider considerations are very important in identifying the content, form, and delivery of user-centered risk communications.

An influence diagram for each chemical sector was developed in four stages: by (1) undertaking a review of literature on the chemical risks; (2) content analyzing existing chemical safety information; (3) conducting semi-structured interviews with occupational hygienists, chemical experts, and toxicologists ($n_{\mathrm{perc}} = 10$; $n_{\mathrm{solder\,flux}} = 8$) working in the UK Health and Safety Executive; and (4) validation of the consolidated influence diagram by a subset of the experts.

We developed our "initial" influence diagrams during Stages (1) and (2), based on our understanding of published expert views on the chemical risks. Then, interviews were held with experts at Stage (3). The interview protocol was structured to elicit expert views in an informal manner. In practical terms, this involved a member of the research team demonstrating the concept of drawing an influence diagram on an unrelated topic, after which the expert would draw his or her own diagram relating to the chemical being considered. The detail of the experts' diagrams varied according to their specialist knowledge and experience. Some were structured similarly to the generic model of Fig. 1. Most experts performed this task with relative ease. A sample expert diagram is reproduced in Fig. 2. Our synthesis of the different experts' individual influence diagrams was supplemented by

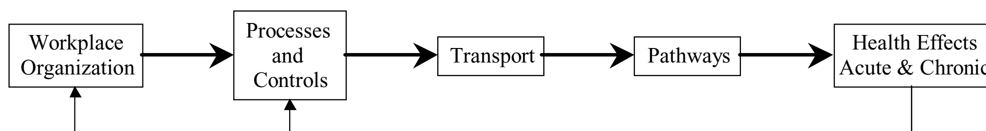

Fig. 1. Generic influence diagram.

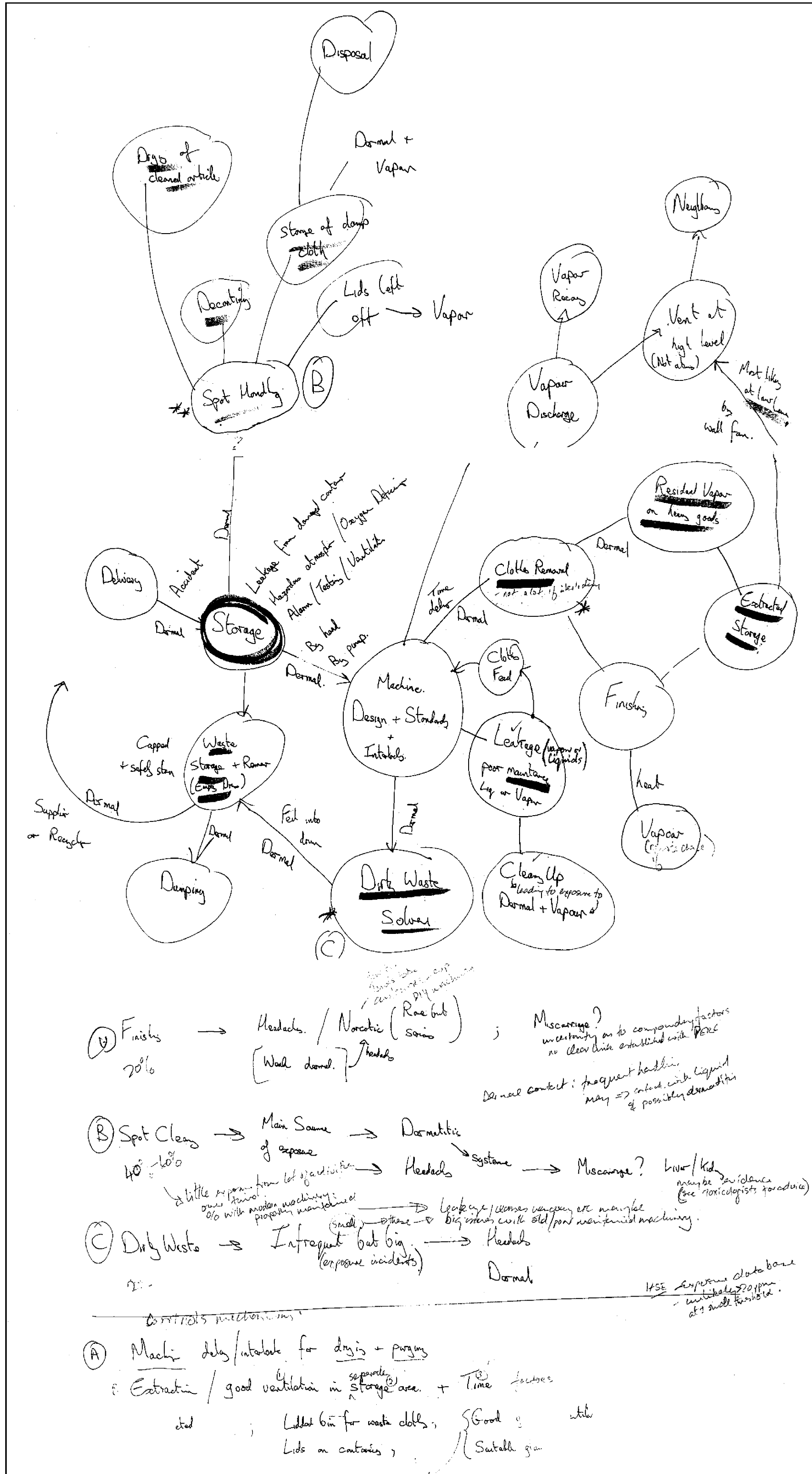

Fig. 2. Sample influence diagram created by an expert (perchloroethylene).

our analysis of the audio recordings of the interviews, together with the understanding gained from the literature review.

At the end of each expert interview, we presented our initial influence diagrams (from Stages (1) and (2)) for review by these experts. Their comments were combined with our analysis of the interviews in the iterative development of the influence diagrams. The experts were also asked to prioritize chemical safety issues and protective measures appropriate to the differing workplaces. In the case of perc, for example, our experts considered preventing inhalation of perc vapors as the primary concern, mitigated by appropriate machinery design, operation, and maintenance. The iterative development of the influence diagrams concluded with an expert critique and validation of the developed versions, yielding the final consolidated influence diagrams depicted in Figs. 3 and 4. These suggest the different concerns that health and safety experts have in the two industrial sectors.

The need to consolidate the elicited expert knowledge in this way inevitably causes the loss of some of the complexity, ambiguity, and uncertainty present in the different expert accounts. This aspect of the study warrants further consideration.

First, iteration is inherent to the methodology proposed here, suggesting that the "final" influence diagrams presented are always *provisional* in nature. For example, changing technologies and scientific understanding of exposure mechanisms and related health effects might refine expert views of chemical risks and appropriate user protection. Furthermore, improved expert understanding of the beliefs, attitudes, and (most crucially) practices of chemical users—obtained through developing "user models" as discussed in Section 2.2—may itself influence expert attitudes.

Second, the influence diagrams shown in Figs. 3 and 4 are *inclusive* by nature in so far as they attempt to provide a comprehensive collective representation of "expert" understanding (literature

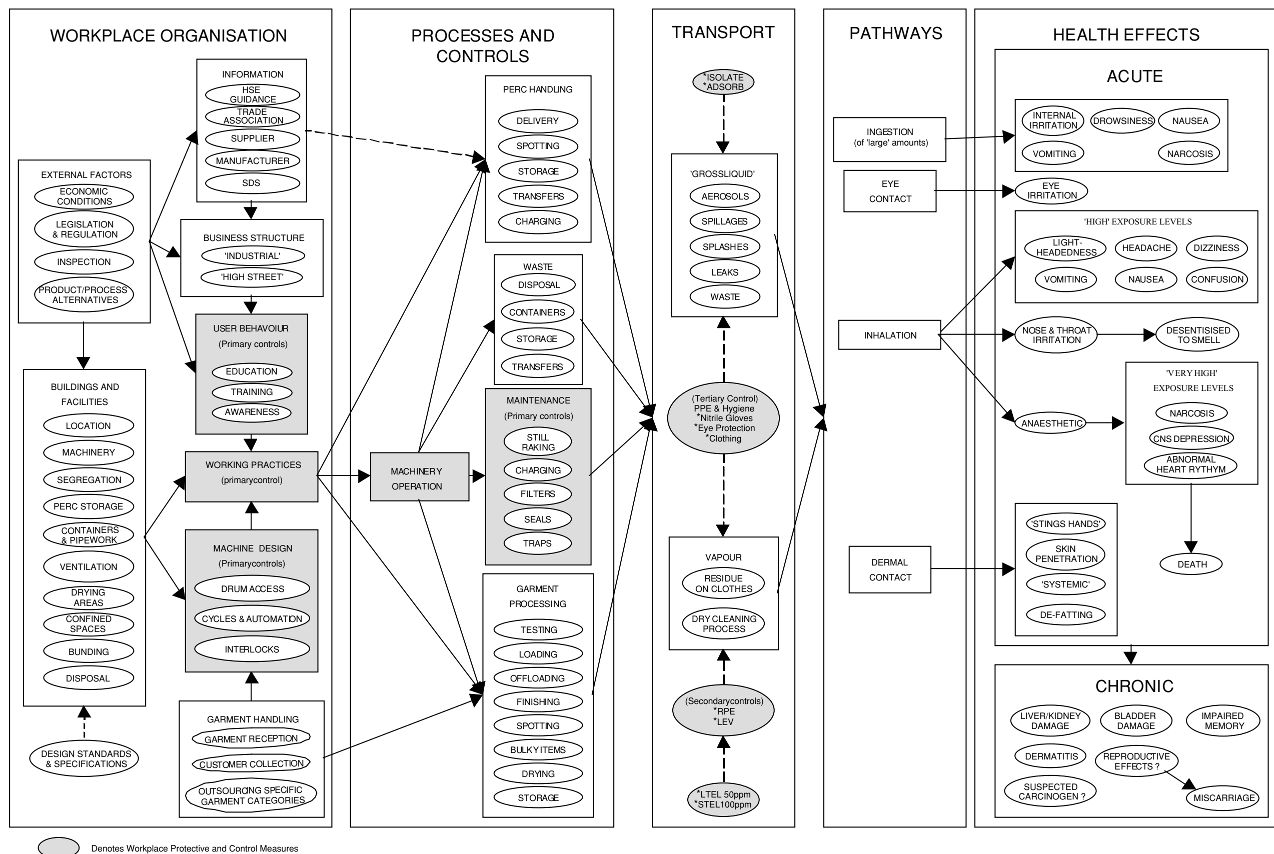

Fig. 3. Expert influence diagram for perchloroethylene.[1]

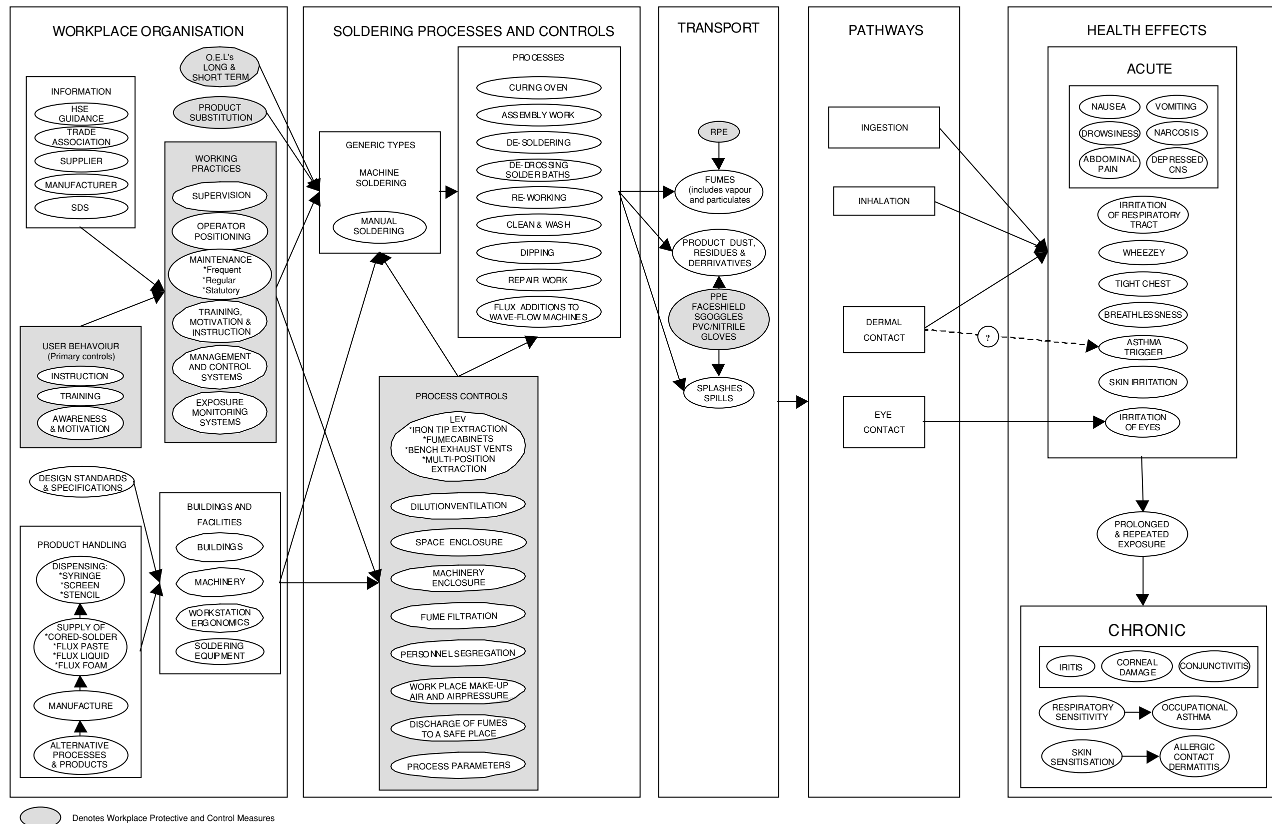

Fig. 4. Expert influence diagram for rosin-based solder flux.[1]

and interviews) of the chemical risks, embracing divergent expert views on the chemical risks where necessary. In our view, the capability to explicitly represent divergence in expert views is an important aspect of the mental models approach. The UK Phillips inquiry[20] into the causes of the BSE disaster makes clear that scientific advice and risk assessment must be capable of accommodating such divergence, and mental models provide a structured approach to achieve this. The subdomains within the expert influence diagrams could be developed further, for example, if a more detailed toxicological risk assessment is required.

Third, in some circumstances the influence diagrams may be adequately developed through Stages (1) and (2) alone, supplemented where possible by Stage (4) in cases, for example, where expert understanding of the risks is already reasonably complete and considerable consensus about the risks exists in the available literature.

In the case of perc, appropriate machinery design, operation, and maintenance were considered to be the paramount issues relating to workplace protection. However, user exposure to perc vapor and liquid arising from "inappropriate" working practices and exposure to accidental spills and releases were also of concern. Experts judged that exposure to perc over long periods may give rise, *inter alia*, to chronic health effects, such as dermatitis, central nervous system (CNS) depression, and liver and kidney damage, while severe acute health effects may result from exposure to elevated levels of perc vapors, particularly in inadequately ventilated and confined spaces.

In the case of solder flux, user exposure to the particulate and gaseous products and byproducts derived from flux during the process of soldering was the principal concern of experts, as the solder fumes were thought to act as respiratory sensitizers, which may give rise over time to occupational asthma. Experts judged, therefore, that chemical protection depends on users' awareness of the hazard and ability to deploy suitable fume extraction equipment in an appropriate manner.

2.2. Developing the User Models

We developed "user models" guided by grounded theory approaches to qualitative data analysis[21] and

based on the analysis of open-ended interviews with individual users of chemicals, who were all either workers or supervisors ($n_{\text{perc}} = 10$; $n_{\text{solder flux}} = 11$). By "user models" we mean the representations of broad user beliefs about, or consensus on, the risks of using the selected chemicals in the workplace, as developed from the individual interviews.

The interview protocols were structured so as to elicit the views of the chemical users with a minimum of prompting from the researchers or influence from workplace colleagues and supervisors. They were conducted in a private setting at the workplace for 20–30 minutes and audio-recorded with the agreement of each participant. The discussions were open-ended and participants were encouraged to talk freely about their workplace use of, or contact with, the chemical in question. Participants who did not volunteer views relating to any of the five significant domains identified in Fig. 1 were invited by the researchers to comment on these aspects. In practice, participants varied in their willingness to discuss issues relating to their own health and their use or "inappropriate" use of the chemical in question in relation their health concerns.

Atlas.ti, a PC-based, qualitative text analysis software based on grounded theory, was utilized to undertake detailed, line-by-line, bottom-up coding of complete interview transcripts.[22–24] As examples, the following comment by one shop-floor drycleaning worker was coded as "high levels of concern" about health effects from using perc: "*You often wonder to yourself, you know, are they safe. Or will that cause cancer later on in life or things like that. I often wonder. That does go through my mind.*" On the other hand, a workplace user of solder flux maintained that "*I did notice after a period of hours you can become sort of like a little bit tired I think. Relaxed, but you know you tend to be sedated, which isn't a bad feeling*," which suggested a "low level of concern" about health effects of using solder flux.

In abstracting from raw data to higher-order categories in this way (and linking related categories together in code networks where appropriate), a structured account of the complexities inherent in the data is systematically built up. This process of abstraction is disciplined by the grounded theory requirement[21] that categories and codes should throughout "fit" (or provide a recognizable description of)[25] the data they refer to. Where labels and terms do not fit, they have to be adjusted and readjusted until a fit is improved.

In grounded theory, abstraction is accompanied by a process of *constant comparison*. It involves continually sifting, sorting, and comparing (raw data, higher-order categories, and, ultimately, the two case domains) for relevant similarities and differences. The two examples cited above suggest very different levels of concern in our two chemical industries, an analytical observation that can then be checked out against other interviewees' statements both about "concern" and about aspects of their understanding (e.g., toward the need for precaution) related to concern. By making such comparisons explicit, the analyst is sensitized to many of the complexities and nuances of meaning or *verstehen* in context[26] across the full data corpus.

To check the fit of the coding schemes produced, all transcripts were analyzed independently by two project researchers, and the resulting coding schemes agreed and finalized through discussion involving the project team.[4]

In this aspect, our approach retains a strong contextual element, in which the user mental model is driven primarily by users' own understandings and concerns.[22,27,28] Thus, the process may be distinguished from the original CMU methodology,[6] which utilizes the expert influence diagram as a structural template to drive the user data content analysis (allowing for revision, when the expert model fails to address user concerns), and from the Goldenhar approach,[11] which conducts structured group sessions to elicit "themes" on chemical risk.

Characteristics of the user models for the two chemical sectors are contrasted in Table II. Table II utilizes a second-order analysis for the organization of information from the user models, under four headings: *concern* about using the chemical, experience of *health effects*, knowledge of *protective measures*, and concerns about chemical health and safety *information*. The four headings emerged out of the coding networks created from the raw data and were used to organize the codes to reflect user views, experiences, and beliefs about the chemical, their work, and their health. In practice, data may relate to several different codes. For example, the experience of adverse health effects (Part B in Table II) might be cited by the chemical users as a reason for their concern about using the chemical (Part A). Alternatively, concern about advice contained in the existing safety information (Part D in Table II) might encourage users

[4] This procedure parallels, but also differs from, more formal "interpreter reliability" checks common with thematic content analysis. Use of the latter depends on *predefining* an exhaustive coding scheme, while in grounded theory the objective is to let the coding scheme emerge from the data.

Table II. User Models for Perc and Solder Flux

Perc User Model	Solder Flux User Model
A. Concern about Using the Chemical	
Concern is medium to high—influenced by user's work experience and perceptions of relative risks.	Concern is low, with visible fumes perceived as the main issue, but considered insignificant and under control.
Acute and chronic are both represented, but chronic effects are the main cause for concern.	Inhalation is considered as the primary concern (related to beliefs about "fumes" generally); dermal contact is not a concern.
High level of knowledge of acute effects, but varied levels of awareness for chronic effects.	Specific health effects are not a concern and long-term effects are not perceived as an issue.
B. Experience of Health Effects	
Direct experience of acute effects is common (headache, light-headedness, rashes, etc.).	Little direct experience of acute effects (rash, sedation, headache, and eye problems).
Experience of chronic effects is low, but nevertheless sometimes acknowledged.	No direct experience of chronic effects.
C. Knowledge of Protective Measures	
The type of machine (design) is considered important for protection, for activities such as unloading and cleaning button trap.	The individual exercises discretion over the use of protective measures, influenced by views about their necessity and efficacy.
Gloves are considered impractical because of the type of work and the need to interact with customers.	The use of gloves, masks, and fume extractors is influenced by practical constraints arising from the type and amount of soldering work undertaken.
Exposure monitoring is not generally undertaken (which may be related to user concerns about desensitization).	
D. User Concerns about Chemical Health and Safety Information	
Safety information about chronic health effects should be clarified.	Users disregard, consider as irrelevant, or have low levels of trust in safety information.
Users' experience of adverse health effects strongly influences their views on the level of uncertainty on health effects in safety information.	Users' views about safety information are influenced by work experience (no evidence of adverse health effects) and their patterns of utilization of the chemical (slow turnover of the product).
MSDSs are the main source of written safety information to users.	COSHH[a] is main source of written safety information.

[a]The Control of Substances Hazardous to Health.

to take protective measures (Part C). In this manner, the organizational headers in Table II attempt to capture the contextual connectedness between codes. As mentioned, the user models as presented here are not wholly inclusive of complexity of individual views, but reflect their predominant characteristics. We discuss each of the four components of the user models in turn.

2.2.1. *Concerns about the Chemicals*

User concerns were very different for the two chemicals. As illustrated in the earlier quotes, in the case of perc, expressed concern was relatively high, influenced primarily by work experience and perceptions of the relative risks. All interviewed users knew that perc was a potentially dangerous chemical. By contrast, concern over solder flux was much lower, with visible fumes being the main issue mentioned by users. Indeed, most of our users did not believe that solder flux *per se* could put them at risk, with many not even identifying flux as a chemical (it is often supplied as a constituent of solder wire or solder paste). Table II shows that beliefs about chemical safety were strongly allied to direct work experiences as well as to knowledge of the chemicals' health effects.

2.2.2. *Knowledge about Health Effects*

Experts consider (Fig. 3) that solder flux fumes may result in acute health effects as well as being linked to chronic respiratory effects possibly through the mechanism of "sensitization."[14,29] This view contrasted sharply with user experiences, as effects, both acute and chronic, were not represented other than through association with extended and uninterrupted periods of soldering activity. In particular, users expressed beliefs to the effect that episodic or infrequent exposure (the norm in many small-scale electronics enterprises) would not constitute a risk and that although (in general) "*smoke can't be good for you*,"

the hazard could be mitigated by "*just moving your head to one side.*"

The expert model for perc (Fig. 3) included a range of acute and chronic health effects as potential results of exposure, although some disagreement remains about the chemical's potential carcinogenicity.[30,31] Users reported (Table II) extensive direct experience of "minor" acute effects (such as headaches and skin irritation), which generally gave rise to low levels of concern ("*not enough to do you any harm*"). User beliefs about chronic health effects appeared more complex. Although a significant driver of uneasiness and concern about perc in the workplace ("*you obviously could have been suffering damage and not know anything about it*"), such effects were typically associated only with long-term "high" levels of exposure to perc. In the empirical data from users, chronic health effects related to extended periods of low-level exposure were either absent or not articulated. Our interpretation is that the concept of cumulative exposure was absent or, where it existed, was modulated by beliefs about the "safe" levels of exposure that could be achieved by adjusting such work practices as washing hands frequently, opening a window, or "*popping outside*" for fresh air.

2.2.3. Beliefs about Workplace Protection

The beliefs about health effects also appeared to influence reported safety behavior and protection in both samples. With solder flux, where the health effects associated with exposure were considered to be infrequent, minor, and trivial (if acknowledged at all), the use of protective measures, such as solder iron "tip extractors" to remove fumes at source, was a matter of individual discretion, relatively relaxed or even circumvented. In contrast, the association of perc with frequent acute effects and the possibility of more seriously regarded (even if uncertain or poorly understood) chronic effects led users of this chemical to endorse strongly the protection afforded to them by the proper operation of drycleaning machines. On the other hand, users cited barriers to other protective measures with perc. For example, the use of gloves to prevent dermal contact was cited as conflicting with current work practices (e.g., the suggestion that users wearing gloves would cause marking on the finished items).

2.2.4. Information

Users' experience of health effects and their belief in the adequacy of protective measures corresponded to their beliefs about the safety information provided in the workplace. Perc users regarded such information as important to their workplace safety, although there was also a range of views concerning how safety information should deal with uncertainty about the long-term health effects of exposure to perc. By contrast, solder flux users generally did not consider information concerning exposure to solder fumes as important.

2.3. Comparison of Expert and User Representations

These results (from the first two steps of the approach) generate rather different first-order representations of the expert and user sets of beliefs. This is seen in the contrast between the experts' relatively well-structured influence diagrams and risk assessment concepts (Figs. 3 and 4), and the users' issues and understandings of the hazard (summarized in Table II, and supported also by the detailed analysis of the user interview data). As noted above, our approach contrasts with the original CMU mental models methodology, where a "template" based on the initial expert influence diagram is used to guide the elicitation and analysis of the user knowledge, thereby facilitating a fairly straightforward "overlay" of the two representations. Our approach forgoes some of this direct first-order comparability in order to remain sensitive to the contextual detail of workers' and supervisors' understandings, as well as to underlying contextual and organizational issues.

However, this does not mean that the two representations (expert and user) cannot be usefully compared. The results of these comparisons are summarized in Table III for perc and in Table IV for solder flux. Each table summarizes, in the first two columns, aspects common to the expert and user models. To structure this comparison, we started with the user models. Specifically, working within each of the four generic headings suggested by the user comments (key *concerns*, *health effects*, *protective measures*, and attitudes toward *information*: see Table II), we interrogated the expert models for information relevant to both the specific user comments and the headings themselves. Clearly, there is an element of judgment in this process. However, we believe that the generic template suggested by the four user headings allows for a systematic interrogation and comparison of the two types of model *without* suppressing the diversity of views. In particular, the comparison is disciplined by the normative objective of identifying the gaps,

Table III. Comparison of Expert Influence Diagram and User Model for Perc, with Suggested Communication Content

Expert Influence Diagram	User Model	Communication Content
Concerns		
Maintain integrity of equipment and controls Concerns over exposure peaks, garment storage & drying, and chemical storage Public exposure issues	Medium-high user concern relates to work experience and attitudes about risks in wider context Chronic effects are of more concern than acute More knowledgeable about acute than chronic effects	Working with perc can lead to serious health problems Machinery gives some protection if maintained properly Constant low-level exposure (loading/button trap etc.) can lead to serious long-term effects
Health Effects		
Acute effects (skin, eye, and respiratory irritant) Contact may lead to dermatitis Chronic effects (CNS depression, liver & kidney damage, impaired memory) Uncertainty on reproductive effects & carcinogenicity	Acute effects (headache, light-headedness, rashes, etc.) common experience Occurrence/experience of chronic effects is rare Vulnerability to different types of PERC and different working practices	Acute effects are reinforced No acute effects does not mean that long-term effects are not going to occur Dermatitis, memory loss, and liver/kidney damage are possible effects after long-term exposure Expert uncertainty persists on issues of carcinogenicity
Workplace Protection		
Protection from vapors provided by machinery design and maintenance Secondary local exhaust ventilation (LEV) is required to control vapors Segregation Dermal controls are considered viable	The type of machine considered to be important for protection (design for unloading, cleaning button trap, etc.) Gloves are impractical because of the type of work and the need to interact with customers Exposure monitoring is not generally undertaken (which may give rise to concerns about possible desensitization)	Keep machinery well maintained If you see a leak, ask! Perc in open containers in the workplace is a problem Doors of drycleaning machines must be kept shut as much as possible Garments must be dry when being handled in any way
Safety Information		
Users require practical guidance Manufacturers of machinery and chemicals have a role in information provision and guidance	Users seek clarity about chronic effects User work experience seems to influence the need to reduce uncertainty about health effects MSDS are main source of written info (COSHH not mentioned)	Skin protection (barrier cream or nitrile gloves) wherever possible

misunderstandings, and correct aspects of users' beliefs on safety, as well as contextual and workplace factors that might constrain appropriate behavior. For example, looking at the user model for solder flux in Table IV, our interviewees reported little experience or knowledge of potential health effects. On the other hand, the expert model identifies several types of health effect (the most important being the link to occupational asthma).

The interrogation of expert models was further supplemented by discussions with domain experts in order to prioritize their most important concerns, health effects, and protective measures. Another possibility, not adopted here, would be to build a formal ranking exercise with the experts into this part of the procedure.

We would not describe this process as an "overlay" of one representation on the other (expert *or* user), but as a structured comparison of the two representations. The implications of this iterative process apply both ways.

On the one hand, the process highlights areas of appropriate user knowledge, user misconceptions, and gaps in user knowledge in relation to the expert model. These provide the basis for designing subsequent risk communications. To take just one example of each: with perc (Table III), both experts and users emphasize the importance of proper operation and maintenance of drycleaning machinery for protection (appropriate user knowledge). In the case of solder flux (Table IV), a common user belief was that solder fumes comprise only the visible plume given off during soldering, and that sufficient protection was afforded by positioning oneself away from the visible plume wherever possible (user misconception). Finally, as noted earlier, with solder flux fumes, there

Table IV. Comparison of Expert Influence Diagram and User Model for Solder Flux, with Suggested Communication Content

Expert Influence Diagram	User Model	Communication Content
Concerns		
More concern for manual than automated soldering Control exposure by LEV at source of fumes Operator positioning (awareness) is important Vapor residues are a concern	Little concern, especially for long-term health effects Users attempt to avoid inhalation of *visible fumes* Direct skin contact is not a concern	Use fume extraction where possible; operatives positioned away from the fumes Extraction equipment is installed and maintained properly
Health Effects		
Irritation of skin, eyes, and respiratory system Fumes may act as respiratory sensitizer Fume inhalation a possible cause or trigger for occupational asthma Dermal contact may be a potential sensitizer	Little direct experience of acute effects (rash, sedation, headache, and eye problems) No occurrence/experience of chronic effects	Fumes are more than just the visible plume Exposure to small amounts may add up in the long term Long-term health effects may result from exposure, including occupational asthma, respiratory and skin sensitization
Protection		
LEV is primary protection mechanism Effective protection against dermal contact is viable	LEV and PPE use is affected by practical constraints Protective measures may be circumvented Individual has control and exercises discretion in use of protective measures—gloves, masks, extractors	Skin contact with vapor residues (dust) is a concern Don't disregard acute effects A magnifying glass may distance an operative away from the fumes
Information		
Promote viable alternative chemicals Better exposure modeling is required Complexity of toxic resin acids (TRA) indicators	Chemical/health information is disregard due to experience at work: little evidence of adverse health effects and periodic/infrequent use of chemical COSHH is a source of information, MSDS is not	Wear gloves wherever possible Consider using *low-rosin* flux

was a complete lack of appreciation on the part of users that even small exposures might "sensitize" a user over time and lead to chronic health effects such as asthma (gap in knowledge).

On the other hand, the user model may highlight areas of expert knowledge that require updating (or at least a reality check) in relation to actual working practices and circumstances. Again in relation to perc (Table III), while users acknowledged the overarching importance of primary equipment controls in protecting (agreement with the experts), they also noted widespread instances of exposure to perc from routine working practices, irrespective of whether the drycleaning machines were operating correctly.

2.4. Prioritizing Communication Content

The prioritization of the communication content is also informed by the iterative comparison of expert and user representations identified under the second-order organizational domains discussed in Section 2.3. Initially, informed judgment is used to prioritize the safety messages and, although not attempted here, this should ideally be supported through an iterative evaluation of the communication.[32] Advice from experts in the respective domains and analysis of user communication evaluation sessions would support the effectiveness of the communication in providing users with information that is necessary for their protection and relevant to the context of their workplace and work practices.[6]

For example, with perc, both experts and users acknowledge the overarching importance of maintaining the integrity of drycleaning machinery and control equipment (see left and middle columns of Table III). However, we also found user indifference or ambivalence to the risk of chronic adverse health effects from exposure to perc other than from the machinery itself. Therefore, we believe that the reinforcement of appropriate user knowledge (the integrity of machinery) should be supported by messages that provide information about the opportunities for cumulative low-level exposure and address user misconceptions about the risks of chronic health affects (see right-hand column of Table III).

In the case of solder flux, a key concern in the expert representation (that fume extraction equipment

should always be utilized) was missing from the user representation (see middle column of Table IV). We interpreted this as arising in part from a gap in user knowledge (that the risk of regular exposure to solder fumes can lead to chronic adverse health effects) interacting with workplace constraints (irritation, noisiness, or difficulty of using extraction equipment). We therefore believe it necessary to prioritize each of these issues in the communication, in terms appropriate to the protection of users and the context of their work practices.

3. CONCLUSION

The article has reported the development and application a generic methodology for understanding beliefs about chemical risks in the workplace. As such, it can provide a basis for developing user-centered risk communications in day-to-day chemical risk exposure. We have shown how an expanded mental models approach captures considerable complexity and contextual richness in user representations and understandings (that go beyond the level of individual "cognition,"[33] including such wider considerations as the work practices that affect understanding of chemical workplace safety and safety behavior.

As with any research process, model validation is important. Influence diagrams could be validated relatively easily, in terms of logical soundness and intersubjective (expert) agreement, through reviews of our final model, continuing the process of revision followed during its development. As noted above, the expert "model" should nevertheless *always* be regarded as provisional, rather than the one "true" or fixed representation.

Establishing the "validity" and "reliability" of user understandings and, therefore, subsequent communication content raises rather more complex issues. The methodological strength of our user modeling rests on the distinctive characteristics of systematic contextual qualitative inquiry.[34–36] As we see it, the goal of all interpretative qualitative research is to develop an account of meanings in relation to their everyday contexts of use. However, this does not mean that researchers can readily or necessarily assume that they have captured a direct *reflection* of their research participants' conceptual systems (in this case the phenomenological worlds of the workers interviewed). In part, this is because some aspects of workplace knowledge (and any influences of this on behavior) are likely to be so routinized as to be "tacit"; [37] aspects of an organization's safety culture may similarly be implicit.[38] Neither is likely to be readily accessible to the type of verbal report elicited by our interviews.[39] A further concern is that interviewees may present an unrealistic (or partial) picture of what they know in response to expectations about what is appropriate to a discussion about safety with university researchers, or where known violations of safety rules are concerned. Accordingly, an ethnographic critique of the interview-based methodology used here would suggest that access to workers' understandings and beliefs can be properly achieved only through extended spells of participant observation. Although this critique might be correct in principle, our own view is that in practice sufficiently useful information is obtained in the interviews to begin the process of communication design. For example, it seems unlikely that a worker who does not mention asthma, or other long-term chronic breathing problems, as a possible health outcome of soldering (and maintains this position under subsequent probing) really possesses this information in any meaningful sense. And while a qualitative study can never be "representative" of either a larger population or its beliefs in the statistical sense, where several individuals drawn from a variety of differing work contexts offer similar responses, one has increased confidence in the conclusions. In addition, in the present study, most of the interviews occurred within the place of work, allowing us to observe, informally, some reported working practices *in situ* (e.g., the lack of use of gloves in drycleaner finishing, and even open drums of perc in one instance).

A more fundamental epistemological issue (present in all research activity, although more visible in qualitative studies) is the researchers' inevitable contribution of their personal constructions of the world to the interpretation of the respondents' accounts.[28] In our case, the researchers' views were likely structured around concepts derived from the expert model. This reflects concern about using the conventional canons of "reliability" and "validity" as criteria for evaluating any research process.[5] Within qualitative research, there is a current debate over if, and which, different criteria might need to establish the "trustworthiness" of research outcomes.[34,41] Four such criteria can be brought to bear on the current work. First, the *coherence* of the user model content (i.e., do the individual columns of Table II provide an internally consistent narrative in the case

[5] We do not wish to enter into the very complex philosophical debates here over the possible differences between qualitative and quantitative research.[40]

of each chemical?). Second, the *contextual plausibility* of the user models, which can be judged in relation to the expert model and what else is known by the researchers and others about the specific workplaces. In this respect, Glaser and Strauss suggest that good grounded theory research should convey a meaningful picture that can be grasped by people because it is rooted in the everyday actions, interactions, symbolism, common-sense knowledge, and human experience making up the social worlds being studied.[21] Third, the provision of an explicit, public *audit trail*, illustrating how raw interview data and key quotes from those data are transformed at each stage of the data analysis. Extended discussion of the raw interview data, and the links to the user models displayed in Table II, are reported in Cox *et al.*[1] A final level of validation involves *direct empirical evaluation by users* of the safety message content (in qualitative research terms, "respondent validation"). For example, users could evaluate statements in the right-hand columns of Tables III and IV in terms of intelligibility, relevance, usefulness, surprise (where a gap in existing knowledge is being addressed), and improvement over existing safety communications. Indeed, we see such empirical validation as an essential part of any structured approach to risk communication design.[32]

In the current case, validation was supported by evaluation of message content by the users themselves. The results of this evaluation procedure were broadly supportive of the communication, suggesting that the methodology was successful in identifying key aspects of user models and, through this, prioritizing message content.[42] In addition, the evaluation process in itself became a source of new user information and should be considered an integral part of this iterative methodology. Morgan *et al.* provide general guidelines and examples for using think-aloud protocols to evaluate communications[6:ch.6] and, through them, the inferred user models.

However, it should be recognized that respondent validation is not philosophically unproblematic and can, in itself, only provide a partial criterion. Demonstrating that the outputs of the modeling process are recognizable and acceptable to participants will represent a validity criterion only when there are clear grounds for believing that interviewees have special insights into the social worlds and issues under study (and in the present case we have already suggested reasons why this might not always be the case). Hence, such commentaries work best if they are treated as further data. Taken as a whole, however, the four criteria of coherence, plausibility, audit, and respondent validation provide a structured basis for evaluating the user models.

Of course, in one sense, communication effectiveness should ultimately be validated against some measure of long-term behavioral change in the target audience. However, this is beyond the scope of the present article and project, and we would argue that the objective of the communication is restricted to providing useable information to workers so as to enable them to make appropriate decisions. Well-informed workers might still decide to take what they consider to be acceptable risks—in the light of the perceived associated benefits.

The current study differs from others using the mental models approach to inform risk communications that have focused on a single risk issue or hazard. By conducting a comparative study, we have been able to demonstrate that the method successfully elicits very different concerns for two different chemical sectors. This suggests that the approach holds generic value as a method, in the chemicals risk domain at least, for targeting communications content for specific chemical use. We believe that the evidence here suggests that the approach can be usefully extended to workplace risk communication for a broad range of commonly encountered chemical hazards. It also provides what we believe to be an inherently *systematic* and *practical* methodology—beginning with the expert modeling, through to the identification of user models and communication content. The work arose from the observation that the current Safety Data Sheet regimes in both Europe and North America do not at present always provide the actual users of chemicals with information they need in a form that they can use. Recognizing these limitations, some regulators and larger companies have produced digested safety information for the direct use of workers. We see the current approach as providing a method for systematically generating such "user-centered" materials (i.e., *intelligible* and *relevant*) as one means of imparting information about workplace chemicals to those most at risk from them.

ACKNOWLEDGMENTS

The research reported in this article was commissioned by the UK Health & Safety Executive under the "3Rs" initiative. However, the opinions expressed in the article are solely the responsibility of the authors and do not necessarily reflect the views of the project's sponsor. We are grateful to Shelagh Molloy

and Marion Evans for their very helpful comments and suggestions. Preparation of the final manuscript was in part facilitated by a program grant from the Leverhulme Trust to the Centre for Environmental Risk.

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