

Toward a theory of multi-modal interaction

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1 Introduction

There has been much recent interest in systems to support multi-modal interaction. The thesis of this paper is that in order for these systems to be successful, we must have a theory of how different media interact with one another and what benefits might be provided by different kinds of media. Currently we lack such a theory.

An early hypothesis for multi-modal interaction was that communication was facilitated by providing multiple channels and maximising bandwidth. However adding visual information was shown to have no effect on communication when speech is available [COPW72, Cha75]. These studies concluded that speech is the critical interaction medium, but they did not say why, nor did they explain the redundancy of visual information. Furthermore, since other studies comparing input modalities conclude that the task might be the most important factor [HG83], we have no way to judge the generality of these results.

In previous research we have contributed toward a theory of multi-modal interaction, although there is clearly much work to be done. Our overall aim is to identify critical features of media that have implications for interaction. One of our claims is that media have strengths and weaknesses in terms of EXPRESSIVITY and that analysing these is necessary for the design of better interfaces [Wal89]. Other di-

mensions such as PERMANENCE and INCREMENTALITY also critically influence interaction. We provide evidence that permanence in media provides benefits not available via spoken language, countering the claim that speech is always the most efficient medium [WBC91]. In addition, while incrementality is a critical feature of communication, we argue that under certain circumstances it may be inefficient to proceed via low level increments.

Finally, despite the emergence of some multi-modal implementations [FM90, Wah90] all of the following present problems:

(1) Although we have the beginnings of theories of Natural Language (NL) analysis and generation, the equivalent theoretical work has not been done for the graphical domain. For input there is no consensus about the reasons for the widespread success of graphical user interfaces, nor about the limitations of these systems [Wal89, SWH⁺90]. The problem is compounded in the multi-modal case by the lack of a theory about how graphics and text interact. Existing systems have relied on heuristics to determine how and when graphics should be presented, when a single medium should be used instead of both media, and which medium this should be [CDM⁺89, SWH⁺90, FM90, Wah90].

(2) Input and output are different: there is more need for a theory for output, because here the system must make a choice about what should be presented. For input, it may be sufficient to offer multiple media and allow people to decide which combinations they want to use. However capacity for mixed-mode input also requires a theory since the

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interface must support integration of the different media, such as by a compatible underlying representation.

(3) New media are beginning to emerge: We will soon have systems that process gestural and speech inputs and allow the use of joint drawing spaces [Bly88, WBC91]. Output will extend to include dynamic media such as speech, video and animation [WD90, BWEK90]. It is unlikely that heuristic accounts will generalise to multiple different media.

(4) Previous work has focussed on mixed-media support for human-computer interaction. There are now new applications where the computer is used as a device to **mediate** human-human communication, e.g to support real-time group work [Bly88, TL88, WBC91].

2 Influences of a Theory of Communication on Multi-Modal Interfaces

Most theories of dialogue argue that the process of communication results in augmentation of MUTUAL BELIEFS, via a process called GROUNDING ([CWG86, CS89], inter alia). Our claim is that different media have different properties with respect to the way they support mutual beliefs and the process of grounding [CB90]. The task of interface design is to combine the set of media that have the appropriate set of features for the given communication situation.

In Clark and Marshall's account of mutual belief, the fact that beliefs are supported by different types of evidence results in them being held with different strengths [CM81]. Physical evidence provides the strongest support for beliefs and linguistic evidence should always be inferior to physical evidence. While we find this account explanatory for a number of phenomena, our claim is that the EXPRESSIVITY of language means that for certain kinds of abstract relational information, physical representation is not the strongest support for beliefs because certain kinds of information are ambiguous in physically-based media, but not ambigu-

ous in language.

Clark and Marshall discuss the grounding of the CONTENT of conversation, while Clark and Brennan discuss the PROCESS by which this is achieved [CM81, CB90]. Interaction is seen as a negotiation process in which participants give and receive evidence for understanding in a manner that is incremental and concurrent. This is made possible in face-to-face interaction by the fact that the available media (speech, gaze and gesture) have certain properties, namely that there is little transmission lag and that each medium allows for duplex (two-way) communication. Concurrency is supported by the fact that there are multiple channels and that each is duplex. Clark and Brennan explore how the grounding of process is achieved when the interaction involves media with different properties than speech, gaze and gesture. They propose features of media such as REVIEWABILITY, REVISABILITY, and CO-TEMPORALITY.

We will focus here on three basic media features: EXPRESSIVITY, PERMANENCE and INCREMENTALITY. EXPRESSIVITY relates to the grounding of content, and is thus orthogonal to the features of Clark and Brennan. We discuss the trade-offs between graphical and language-based interfaces for EXPRESSIVITY in section (3). Our PERMANENCE feature is an abstraction of the revisability and reviewability features. In sections (3) and (4) we discuss how permanent media support grounding of content, whereas ephemeral media are better for process. To support both content and process a mixture of both PERMANENT and EPHEMERAL media is optimal. Finally our belief is that INCREMENTALITY is a function of other attributes such as low latency and the availability of concurrent duplex channels. In (3), we discuss process and argue that while incrementality is critical for grounding, communication can become inefficient if increments are low level.

3 Expressivity of Graphics and Language

3.1 Graphically-Based Interfaces

Since the advent of the Xerox Star, graphical user interfaces have enjoyed great success. They are based on a set of principles for so-called Direct Manipulation Interfaces (DMIs): (a) continuous representation of the objects and actions of interest, (b) physical actions or labeled button presses instead of complex syntax, (c) rapid incremental reversible operations whose impact on the object of interest is immediately visible ([Shn86]). These are claimed to be unique to the graphic medium.

In terms of a theory of communication, it is clear that (a) and (b) and a large part of (c) can be viewed as specific instances of the claim that physical evidence provides the strongest support for beliefs. This is true of facts that can be conventionally signalled by purely visual means. The only thing remaining is the portion of (c) having to do with ‘rapid, incremental, reversible operations’, but these features are certainly not specific to graphically-based media. Indeed grounding theory claims that being rapid and incremental are critical features of face-to-face interaction. So it seems that the principles of DM may be reducible to grounding in communication. We will have more to say on INCREMENTALITY in section 3.3.

Furthermore, while proponents of DMIs have been very vocal about their benefits, very little attention has been drawn to their limitations. Our feeling is that these limitations are inherent in any graphically-based medium. In order to elucidate these limitations we will focus on the strengths of language-based media.

3.2 Language-Based Interfaces

Language takes us out of the realm of the **here** and **now**, visually present. The claim here is that NL provides communicative benefits for the EXPRESSIVITY dimension that are difficult to realize in terms of concrete manipulations on physical objects, as in DMIs, or difficult to express via

graphical output alone using diagrams, pictures or animation [WD90, BWEK90]. In earlier work, we analysed input to a desktop style interface [Wal89], but we will extend the analysis to output here. The features of the analysis are called COMMUNICATIVE FEATURES. Some of them have to do with being able to refer to objects with language rather than directly, which is possibly more useful for input to a system, rather than output. However for multimodal output, descriptions can draw attention to particular aspects of physical or other attributes that are relevant for the purpose at hand. Some of the features relate to the flexibility of the interaction with the system, and as well to **how** actions are to be carried out. The features are¹:

- **DEFINITE DESCRIPTION:** Linguistic input allows one to refer to an object, via a description without having to see it. DEFINITE DESCRIPTION supports access to objects by their attributes, e.g. *find the file whose write date is 8/15/88*, instead of solely by visual searching. It is difficult to represent graphically because of the problem of abstraction: If an instruction for an operation depicts a red folder of a certain size at a certain screen location, which of these properties should the user abstract as being the critical ones for success? Will the operation work only for folders, or red folders, or red folders that happen to be located there?
- **DISCOURSE CONTEXT:** The use of a pronoun such as *they, it, their, him* allows one to refer efficiently to previously evoked objects. For instance, *Create a file named Jazz. Send IT to Susan.* By allowing questions to range over a set of objects gathered as the result of some previous command, e.g. *Get me the messages from Eric. Are any of THEM about today's meeting?*, discourse reference allows one to simultaneously point to multiple, not necessarily visible, objects. Another critical property here is that ability to refer to actions, via pronouns or by ELLIPSIS: *Give me last year's sales by month. Do IT again for 1989.* DMIs have no means to represent or manipulate actions in this way.

¹This list is not claimed to be exhaustive, but is an initial step toward a taxonomy.

- **TEMPORAL SPECIFICATION:** This allows the representation of temporal relations between actions, such as that an action should take place at some time in the future, or repetitively, or simultaneously with another action. For instance in output, one might want to express relationships such as *While doing X, do Y*. An example for input would be, *Send CHIDraft to Jarrett ON MONDAY* or *Send a copy of the proposal to Susan EVERY WEEK*. Current DMIs employ techniques such as calendars and time lines, although as we shall see the use of these is far from intuitive.
- **QUANTIFICATION:** Quantifiers like *all, every, each, any, some, most, how many, how much* support access to global properties of a system. At input users can get information about the state of the system without visually inspecting it, e.g. *HOW MANY folders named AAAIDraft are there?*, or *Are there ANY files whose write date was yesterday?*. On neither occasion is there a need to inspect the contents of the file drawer. Quantifiers like *all* and *every* support operations on sets of items, e.g. *Send a copy of proposal-1 to EVERY person in the dialogue project*, without the need for multiple single operations. For multi-modal output, it is more felicitous to say *ALL the switches have been turned off* rather than to show each switch being turned off in turn, because the critical information to the user might be that there are no activated switches.
- **COORDINATION:** This is exemplified by coordinators like *and* and *or*. Users can specify the same operation on more than one entity at a time, e.g. *Send the ACL-draft AND Phil's message to Steve*, or specify different operations on the same entity, e.g. *Latex file Jazz AND print it*. Coordination can be used to implicitly create sets of objects that do not share any obvious attributes other than that the user chose to group them. Currently cues such as spatial grouping are used to depict set membership in DMIs although clearly this cue is ambiguous.
- **NEGATION:** This is exemplified by words like *not, except* and *without*. For any pictorial response to a question, it is difficult to highlight the absence of a relevant attribute. In the desktop application, it also allows one to collect desktop items that do NOT have a particular attribute or to exclude particular items from a set. An example might be *Are there any messages I haven't answered?*
- **COMPARATIVES:** These range over attributes or quantities of the domain objects of interest, as in *Are there any messages OLDER than two months?*, or e.g. *Are there MORE THAN two messages from Eric?*. Despite the fact that the attributes of interest are often **physical** attributes, it is quite difficult to unambiguously indicate the comparison scale of interest with only graphical output.
- **ACTION MODIFIERS:** These are often present in language by the use of *by* or *in* phrases, such as *by date* or *in a graph*. For example, *Show me the messages in my in-tray by topic*. Adverbials such as *slowly* or *carefully* also allow the further specification of actions. This allows control over **how** an action should be carried out, and clearly is very difficult to specify via pictorial means.
- **SORTAL ABSTRACTION:** This aspect allows linguistic input to be nonspecific, so that one could ask *Are there any paintings with birds in them?* and the system might respond with, e.g., paintings that have crows, sparrows or eagles in them. If this response is merely pictorial, the relevant level of abstraction may be ambiguous to the user. For instance, an instruction that makes use of a container may have to be instanced pictorially as using either *a cup* or *a bottle*, thus losing the abstraction in the original description.
- **CONDITIONALS:** Conditional relations between actions are difficult to express through a graphical/physical channel. If one wanted to depict graphically *Only flip the switch if the light is ON*, it is difficult to express which aspects of the depicted scene critical. The problem becomes especially acute when there are complex relations between events.

- CAUSALITY: Similarly to conditional action, causal relationships between actions and events cannot easily be expressed via graphical means: *When you push the button, that will turn on the light.*

3.3 Empirical data for mixed-mode Human-Computer Interfaces

We have used the analysis in sections (3.1) and (3.2) as the basis for some prototype multi-modal interface designs, as well as for the analyses of some user studies and experimental data.

We conducted a field study analysing system use by a group of 50 managers who had a choice of using a menu-based interface or a natural language interface to access a database of information about orders and sales[WW89]. We considered the selection-based menu interface to be a competing mode of interaction with the restricted NL query system. Our focus was on the usage of the NL in preference to the menu system to find the specific features these people were using. Persistent users exploited the fact that NL allowed them to specify **how** the action should be carried out (ACTION MODIFIERS), so that they could sort the presentation of the data or request it in various graphical formats. The fact that they could control the granularity of the data presented through some simple forms of SORTAL ABSTRACTION made the graphical capabilities of the system much more useful. Users took advantage of the fact that they could use COORDINATION to (a) construct ad-hoc sets of objects and (b) construct complex queries out of constituent simpler queries. They also exploited the capacity of the interface to keep track of the current DISCOURSE CONTEXT in order to understand elliptical action descriptions.

The second application of the feature set was to the design of a multi-modal information retrieval system for budgeting information[SWH⁺90]. The system attempted to combine the strengths of NL and DMIs, by graphically depicting a set of conceptual models. These not only represented valid lexical items for NL, but could be used for direct graphical query. The system also depicted the results of each query as a set of objects which were

available for re-use in further queries: A user could point to a set of reports using a gesture and then ask a question about that set, e.g. *Which of these are greater than \$10,000?* By preserving the results of each query as discourse context, the system supported query at multiple levels of abstraction. A knowledgeable user could ask in a single NL query for *all the reports from Project X, that are not for 1989.* The same result could also be produced from a series of successively more specific queries each of which re-used the results of previous queries. Another function of the features list is that it enables NL system developers to focus their efforts. If it is not desirable to develop a broad coverage NL system, then one can focus on the aspects of the graphics system where NL really gives added value: namely those things which are difficult to do using graphics.

The third investigation of the proposed trade-offs between different media for input was in a study of 6 users in a desktop environment. They had a choice of using DM or a simulated NL (using the Wizard of Oz technique, WOZ) to accomplish tasks in a complex distributed filing system. One result was that there was a high degree of NL use when there was a choice of input modes. Surprisingly, subjects sometimes preferred NL even for very simple tasks/actions, such as opening a document, which could be achieved using a single mouse click. The proposed utility of QUANTIFICATION and DEFINITE DESCRIPTION to avoid laborious search through nested document folders was born out, with typical requests being *Get me all the documents from folder A.* People also made use of NL to file objects away. This exclusive use of NL for finding and filing in the Desktop suggests that the use of physical search in DMIs (by recursively opening folders) may not extend to complex filing systems. The result was a reduction in the utility of the spatial/graphical metaphor for Desktop organisation and operation[Whi90].

In another experiment, the tasks were designed in order to favour the use of the NL features(3.2)[Jon90]. This experiment gave subjects a choice of using an implemented graphical interface or a simulated NL interface(WOZ). Subjects preferred natural language to the graphical interface for the specification of temporally depen-

dent actions (TEMPORAL SPECIFICATION), and for selecting objects depending on a set of complex attributes (DEFINITE DESCRIPTION). Even users experienced with the graphical interface preferred to use NL when given a choice, despite a 25% failure rate with NL.

3.4 Summary

The weaknesses of graphical interfaces (e.g. DMIs) relate to EXPRESSIVITY in two distinct ways. The first is that there are certain types of abstract relations that are fundamentally difficult to depict rather than to describe. The second concerns abstraction: while operations such as finding and filing are achieved as a result of incremental operations using direct manipulation, it seems that efficiency dictates that we need to support larger granularity actions. Our mixed-mode system also allowed reuse of previous query. We will discuss the utility of the PERMANENT conversational record in the next section.

Other researchers working on mixed-mode interaction ask: *How is the explanation content to be divided among different media such as pictures and text*[FM90]? They divide information based on heuristics such as: location physical information in graphics only, simple and compound actions in text and graphics. Our view is that while these heuristics are approximately correct, they will not generalise to other situations. Our features predict that the desirability of graphical vs. textual display depends on other factors such as how abstract the physical attributes are, or whether they are inherently relational as in the COMPARATIVE: *Bill is taller than Fred*. This type of comparison cannot easily be demonstrated with pictures of Bill and of Fred only.

4 Interfaces for Mediated Interaction

The previous discussion has concerned human-computer interaction but the same issues arise for a new type of system that **mediates** communication between people[Bly88, TL88, WBC91]. What

is needed are guidelines for the design of new mixed-media interfaces. Current claims for mediated communication are that speech is inherently superior to other media for real-time interaction. Despite the utility of speech in the grounding process, one problem with speech is its ephemeral nature. We therefore conducted a study to investigate the effects of PERMANENCE on mediated interaction[WBC91]. We looked at mediated communication using a shared electronic Whiteboard *with* and *without* the addition of a speech channel. People who used only the Whiteboard were forced to rely on communication using a permanent medium such as typing or drawing. Those who had speech as well as the Whiteboard had the choice of permanent and ephemeral media. We found several advantages to permanent media: they allowed users to abandon some (but not all) of the turn-taking commonly used in spoken conversation and to organise their activities in a highly parallel manner. Permanence meant that users were not compelled to respond immediately to inputs from other users: they could complete their current activity knowing that the relevant input would persist. Other advantages of the permanent medium was that it allowed the use of space to signal relations: People tended to place related items in the same physical location in a way that is impossible in ephemeral media. Finally the permanent medium allowed people to construct a physical record of the conversation, not only did this serve to record group decisions and preserve the context of conversation, but it also served as the target for deictic pointing: *What do you mean by THIS?* where the target for the gesture is written material. Despite these advantages of permanent material, however, one problem that arose with ephemeral media was the need to agree when to delete material.

When we added the speech channel to the Whiteboard, people still used the Whiteboard for part of their communications. This result suggests that claims about the inherent superiority of speech for communication are simplistic[COPW72, Cha75]. The Whiteboard was still used as a means to record data, even though it required greater overhead to produce typed or drawn material for the Whiteboard compared with producing speech. We also found that different aspects of communication were

allocated to the permanent and ephemeral media. The Whiteboard was used for data recording, i.e. the **CONTENT** of the communication. However it was never employed for processes like **CLARIFICATION** and **NEGOTIATION**: These aspects of communication require rapid speaker switching, with consequent demands on timing and this coordination cannot easily be achieved with typing or drawing.

Other research has also looked at the interaction between permanent and ephemeral media and shown that ephemeral media such as gesture are critical in collaborative design activities[Bly88, TL88]. One critical function of gesture is to achieve reference to materials already created in permanent media and these accounted for 60% of user activities in one study[Bly88]. The advantage of gesture over other means of achieving reference is that it can be used to identify things that are difficult to describe. For example *the part of the drawing that is half obscured by the circle* can be identified by a single gesture. Graphical annotations could also do this, but the ephemeral nature of gesture means it does not have to be deleted when reference has been successfully achieved. In conclusion, our research has shown that claims about the superiority of speech in mediated interaction have neglected the utility of **PERMANENT** media: Speech is useful for grounding **PROCESS** but writing and drawing can serve to ground the **CONTENT** of communication.

5 Conclusion

We have claimed here that there is a lack of theory as to how mixed-mode interfaces should be designed and we have tried to show that the beginnings of such theory must come from considering the **communication** requirements of a given situation. The second claim is that different media have different communication properties. We have attempted to suggest some of these features and show their influence for both human-computer and computer-mediated communication. More work is needed to refine this feature set in order that appropriate combinations of media can be presented to facilitate communication. We also need to understand how different media interact and the set of cases in which they actually interfere.

While it might be argued that anything that can be done in one medium can be done **somehow** in another, we must avoid what has been called the *Turing tarpit* [HHN86]. While proponents of graphically based interfaces may claim that all that is needed are new icons for **QUANTIFIERS** and **TEMPORAL SPECIFICATION**, studies have shown that workarounds for the temporal dimension such as placing items on a calendar were not intuitive for users[Jon90]. Also while it might be possible to represent sequences of events with animation or video, the dependencies between the events are often less than clear; currently the expertise in clearly representing the relations between dynamic visual events is only possessed by a small number of people in the film industry. Indeed claims about the inherent superiority of one medium over another miss the critical point that by mixing modes we can capitalise on the strengths of multiple media.

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