realistic machine imagery which can simulate in detail the light pattern presented to the retina by objects yet to exist? Inspired by James Gibson's "ecological" theory of perception (Gibson 1979) that denies the importance of mental representation, this appears to be the philosophy behind some "virtual reality" design systems (Smets 1992).

Although the usefulness of very realistic modelling systems for the late stages of design is undeniable, I believe that to discard (in machine systems) the untidy, hand-drawn indeterminacies and vagaries of "back of an envelope" sketches before we understand their function would be self-defeating. Neither is blind machine simulation of media attributes an answer. (I nickname this the "imitation bronze" approach, after those early Han period Chinese ceramics that tried to imitate bronze vessels.) Without at least a theory as to how paper sketch attributes support design, it is impossible to design appropriate machine replacements for the humble sketchbook.

I have specified elsewhere many ways in which a machine sketching system might improve on the functions of untidy paper sketches (Fish 1996). Not the least of these would be an improved facility for descriptive to depictive translation. This would include the representation of visual tolerances with machine assistance in progressive refinement as the mind explores branches and twigs of the design decision tree. Using a hierarchy of descriptive to depictive two-way pointers, machine memory can represent, below the visible surface of the sketch, a much richer and complex part of the design decision tree than is possible with older media. The evidence concerning working memory capacity suggests that sketching technology should do more than it currently does to protect our linguistic and visuo-spatial memories from trampling on each other's resources. It is easier to listen to ideas and visualize a design at the same time than to read about ideas and visualize a design. Current technology should make it easier to combine the descriptive and depictive components of our thoughts without their mutual interference.

But before such much needed descriptive to depictive translation support systems can be well designed, we need to answer questions about the philosophy of visualizing technology. For example, "Do we wish to amplify or to replace our visualizing ability with machine processing in the early stages of design?" If the cognitive catalysis theory is correct, then we cannot achieve both these objectives at the same time. Very detailed "virtual" representations would be expected to hinder rather than support the user's inventive imagery and mental translation processes. I believe cognitive amplification is a better design philosophy for sketching systems than cognitive replacement. It is in the nature of the visual arts that there must always be a part of a designer's mental image that cannot be represented by machine because it cannot be made explicit.

Another question concerns education. The evidence from prehistoric painting and sculpture, combined with the evidence from 21st-century cognitive science, shows that we cannot reason inventively, even about non-visual things, with symbols alone. Our brains have powerful resources for thinking depictively, but these can only be fully tapped if our culture can provide an appropriate visualizing technology and teach us to use it. This it has not yet done. The need arises because imagery capacity is still so closely tied to perception.

It has been known since Simonides in 500 BC (Yates 1966), that imagery can be used to augment verbal memory. However, the ability to create

personal incomplete images that catalyze mental descriptive to depictive translation is a skill that deserves to be taught and practised as urgently as reading and writing. In a paper presented to a conference on "The Future of Drawing in Design" Professor Bruce Archer has argued that it is not just students of the visual arts who should be taught the art of sketching but all pupils (Archer 1997). "Drawing is indeed a great deal more than a training for the hand. It is a great deal more than a training for the eye. It is indeed a training for the mind . . . On these grounds we can argue for the strengthening of its place in the National Curriculum and the confirmation of its place in entry requirements at tertiary level." Later he concludes: "I would further hypothesize that for those going on to study for any creative or inventive occupation, instruction and practice in creative vagueness should continue until at least the end of the first undergraduate year." To this bold statement I can only add that, if we are to teach all children to use more fully their under-exploited visualizing instincts, then we need to improve the quality and scope of our sketching technologies. It could be argued that the failure, as I see it, of our culture to exploit fully our innate visualizing capacity is a consequence of the emphasis that a science-based culture must give to symbolic thought. The language instinct probably evolved as an accessory to the older visualizing instinct. We have now reversed the roles of these two instincts so that mental imagery is more often perceived as an accessory to language.

If the analogy of sketches to mental catalysts is apt, then progress in the design of visualizing systems will be tied to progress in cognitive science. Sketches, it is claimed here, are not representations but representation support structures. They can only be understood by understanding the mechanisms of thought and how 30,000 years of cultural evolution have taught us to use our brains in ways for which they did not evolve. Untidy sketches provide some of the evidence. A drop of water reflects the ocean.

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Figure 7.4 is reprinted from Lawson (1994), by kind permission of Butterworth Heinemann, Oxford.

Notes

1. How language evolved is still a much-debated topic. For an excellent discussion of the relative roles that inheritance and culture might play in the evolution of language acquisition skills, see Deacon (1997).
2. I have necessarily oversimplified the complex arguments about the relative influences of genetics and culture on the evolution of our brains and how they work. For those readers who agree with me that this question is relevant to both how we design and how we teach the use of "mind-tools" for design thinking, the following works are recommended: Donald (1991), Durham (1991), and Mithen (1996). Each provides a different perspective on how