Students may produce simple drawings that are similar in appearance (Figure 4) but mask wildly different mental models of the circulatory system. Figure 4a (Student A27) shows arrows entering the right and left atria at the top and arrows exiting the ventricles at the bottom. While pointing gestures index drawn and labeled elements such as the chambers and walls, no explanation of a time-varying process is provided, resulting in a very low score for the model (2 points out of 6). In contrast, Figure 4b (Student A14) shows a very similar drawing, with less detail (no labels) but through gesture and speech provides a rich account of the blood flow following two distinct pathways (from heart to lungs and back, and from heart to body and back) that receives a high score (6 out of 6 points). As Figure 4c shows, A14's gestures dynamically simulate blood flow to components of the system (e.g., lungs, body) that are not present in the drawing, but are invoked by gestures that move beyond the boundaries of the page.

Several insights emerge from the analysis of students' drawings and explanations. Methodologically, drawings are only a part of a student's rich, multimodal construction and must therefore be assayed in the context of the associated verbal and nonverbal information. Other examples show that even elaborate diagrams with arrows and labels suggesting the occurrence and direction of dynamic processes have limited assessment value without co-expressive gestures and utterances. As part of an emerging theory of the nature and functions of drawings for knowledge assessment, we find that these multimodal constructions (*psychological units* to Vygotsky, 1986; *growth points* to McNeill, 1992; *composite signals* to Engle, 1998; and *semiotic nodes* to Radford et al., 2003) are particularly evident when conveying time-varying phenomenon and causal relations.

Interactive drawing tools to support modeling of dynamic systems

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Dynamic computer modelling is a valuable way to learn about complex dynamic systems (Löhner, van Joolingen, Savelsbergh, & van Hout-Wolters, 2005; Spector, 2000). In a modelling task, students create an executable model in order to build and express their understanding of scientific phenomenona. Once the model is built, the data it produces can be compared to the expected or observed behaviour. The model can be modified depending on the outcome of this evaluation (Penner, 2001). Despite its benefits modelling is often experienced as difficult for students. For instance, students often fail at successful modelling behavior, because they do not use their prior knowledge while working on an inquiry modelling task (Sins, Savelsbergh, & Van Joolingen, 2005). Such observations highlight the need to support the modelling process. In the present paper, descriptions of drawing sketches of the modelled system as a means to support modelling are presented. Two approaches can be distinguished: drawing to prepare the model and drawing the model itself.

When drawing to prepare the model, a sketch serves a supporting and assisting role prior to "real" modelling. A sketch can be used to identify relevant variables and relations between variables. Figure 5 displays a sketch of a water tank that is then converted into a System Dynamics model. The drawing helps the learner to identify the relevant variables in the system, such as water level and outflow. These variables can then be converted into variables in the model. The drawing helps in this way with activating prior knowledge, and in constraining the model, based on the drawn elements. A sketch-based modelling tool can provide support in transforming a sketch into a model for instance by labelling model elements in the drawing.

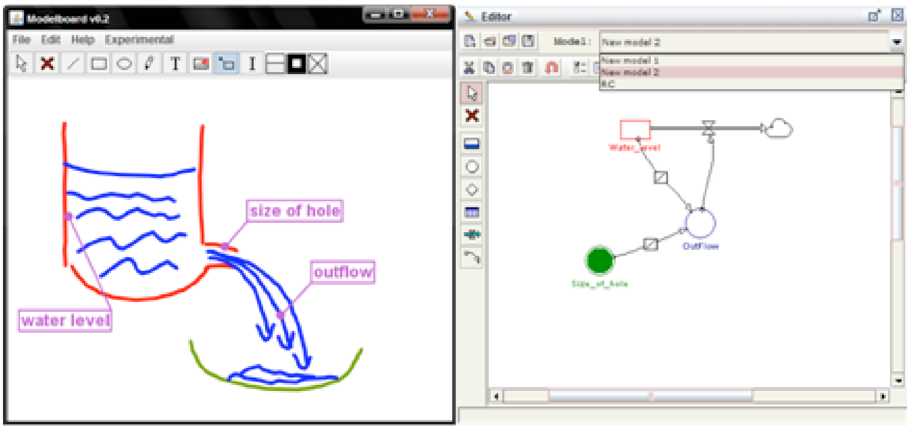

Figure 5. A sketch as a preparation for a (System Dynamics) model.

In order to investigate the suitability of this approach, we asked 68 students in upper secondary school to create drawings about the thermodynamics of the Earth: the earth is heated by the sun, making the earth radiate heat that is absorbed by the atmosphere, resulting in an equilibrium temperature. Close analysis of these drawings, identifying drawing elements and using principle component analysis shows that drawings give clear indications of learners' main views on heat and temperature, diverging into a radiation view and a heat transport view (Kenbeek, Van Joolingen, & De Jong, submitted), yielding complementary sets of variables to include in the model. Apparently drawing guide learners in making their views on the domain more explicit.

Alternatively, the learner-created sketch can be regarded as a model in itself. The drawing will not be transformed into another representation, but it is fully qualified as a learner's external representation of a phenomenon. In this case the drawing must adhere to some formal aspects, such as clear identification of objects in the drawing and their properties. Forbus and Usher (2002) put the burden of doing this with the learner who needs to identify the start and end of drawing and object (glyph in their terminology) and select a term from an ontology to describe the object. The approach presented here automates object identification by clustering strokes based on time, position, color and weight. A 95% agreement with human raters is reached using this method based on a set of drawings created by 37 students on two domains, a toy car (e.g. Figure 6) and a heating system (Leenaars, Bollen, & Van Joolingen, submitted). Sketch recognition techniques (Paulson & Hammond, 2008) can then assist object identification which can result in a formal model.

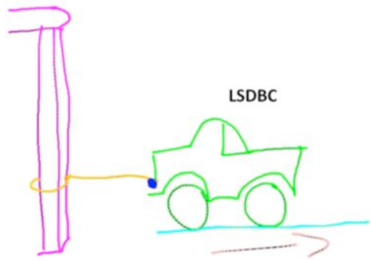

Figure 6. Drawing of the toy car system. Colors indicate automatic clustering results.

These two approaches provide a promising outlook on the use of drawings to support the complex task of modelling. The drawings collected in the two studies – for different purposes and in different domains, show that they are interpretable and give insight in learners' ideas about the domain modelled. Together the two approaches form a set of stepping stones that can be used to support the development of a modelling competency by novice modellers.

References

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. Learning and Instruction, 16(3), 183-198.

Ainsworth, S. E., & Loizou, A. T. (2003). The effects of self-explaining when learning with text or diagrams. Cognitive Science, 27(4), 669-681.

Alesandrini, K. L. (1981). Pictorial—verbal and analytic—holistic learning strategies in science learning. *Journal of Educational Psychology, 73*, 358-368.

Ardac, D., & Akaygun, S. (2004). Effectiveness of multimedia-based instruction that emphasizes molecular representations on students' understanding of chemical change. *Journal of Research in Science Teaching, 41*(4), 317-337.

de Jong, T., & van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research, 68(2)*, 179-201.

Chi, M. T. H. (2000). Self-explaining expository texts: The dual processes of generating inferences and repairing mental models. In R. Glaser (Ed.), *Advances in instructional psychology* (Vol. 25, pp. 161-238). Mahwah, NJ: LEA.

Engle, R. A. (1998). Not channels but composite signals: Speech, gesture, diagrams and object demonstrations are integrated in multimodal explanations. In M. A. Gernsbacher & S. J. Derry (Eds.), *Proceedings of the Twentieth Annual Conference of the Cognitive Science Society* (pp. 321-326). Mahwah, NJ: Erlbaum.

Flower, L., & Hayes, J. R. (1981). A cognitive process theory of writing. College composition and communication, 365-387.

Forbus, K. D., & Usher, J. (2002). *Sketching for knowledge capture: A progress report.* IU'02, San Francisco.

Gobert, J., & Clement, J. (1999). Effects of student-generated diagrams versus student-generated summaries on conceptual understanding of causal and dynamic knowledge in plate tectonics. *Journal of Research in Science Teaching, 36*(1), 39-53.

Hegarty, M., Kriz, S., & Cate, C. (2003). The roles of mental animations and external animations in understanding mechanical systems. *Cognition and Instruction,, 21*, 325-360.