Text Entry

Modelling and Design

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Design and AI Engineering

- **Design engineering** (or engineering design) is a set of design methods for systematically designing, building, maintaining, supporting, and decommission products
- **AI Engineering** is largely seen as somewhat of an extension of software engineering where additional process aspects should be attached for better results
  - Bosch, J., Olsson, H. H., & Crnkovic, I. (2021). Engineering AI systems: A research agenda. *Artificial Intelligence Paradigms for Smart Cyber-Physical Systems*, 1-19
  - Ozkaya, I. (2020). *What is really different in engineering AI-enabled systems?. IEEE Software*, 37(4), 3-6
- In my view it *should be* about the process of designing, building, maintaining, supporting, and decommissioning a system infused by artificial intelligence

What's in a *system*?

- When you open a door, pull down the handle and pull the door open you are interacting with a system
- The door handle is a system consisting of fittings, screws, a plate, a handle, and it is interacting with another system—the door itself
- The door in turn, is interacting with the wall it is mounted on using hinges, and the door frame itself might even be load bearing
- The user opening the door is attempting to reach a goal state, to that of the door being open, and is doing so by planned movements executed by the user's human motor control system
- The action of the door being opened is monitored by the user's visual and auditory systems
- At the cellular level, neurons and synapses form complex systems carrying signals through the human body to enable perception and action
- The screw is part of an intricate design, manufacturing, and logistics system, which includes designing the screw, efficiently producing it, packaging it, and distributing it
- Doors are subject to regulation, in particular building control regulation, which will specify, among other things, acceptable dimensions, such as the door width for accessibility

Why AI engineering is hard

- Building a **system** is hard!
  - Complexity
  - Tight coupling
  - Emergent properties
- Building an **interactive system** is even harder!
  - Now we have to worry about users!
- Building an **intelligent interactive system** is even worse!
  - Now we have some AI component that behaves in a non-deterministic way
  - New design issues arise: control, interpretability, and agency
  - Have to worry about governance issues of AI (safety, fairness, regulation, etc.)

What does design engineering tell us about AI-infused system design?

Five design engineering approaches

- Establishing *system boundaries*
  - Deciding what the overall *concerns* of the system are
- Separating *functions* and *function carriers*
  - Focusing on *what* needs to be done rather than *how* to do it
- Decomposing *overall functions* into *function models*
  - Establishing *relationships* between functions before considering solutions
- *Parameterizing* function models
  - Attaching *controllable* and *uncontrollable* parameters to a design at a functional level
- Carrying out *envelope analyses*
  - Generating hypothetical *operating points* to understand the *mechanisms* underpinning estimated performance as a function of the parameters

Establishing *system boundaries*

System boundary

- A **system boundary** is a very simply concept
  - The delineation of concern for the analysis of a system
- Setting a system boundary means capturing all elements necessary for analysis
  - Such as user interface, machine learning system, training data, user, etc.
- Analysis now bounded by the system boundary
  - This ensures risk analysis is tractable and assesses all relevant factors
  - This ensures intelligent interactive systems actually capture **all essential factors**

Example systems to consider

- A wearable fall-detector system to detect likely falls among vulnerable patients in a hospital
- An infusion pump allowing patients to self-administer pain relief based on a drug dose set by a nurse on a doctor’s recommendation
- A wearable helmet allowing rapid triage for brain trauma following an explosion
- A spell checker
- A spam filter

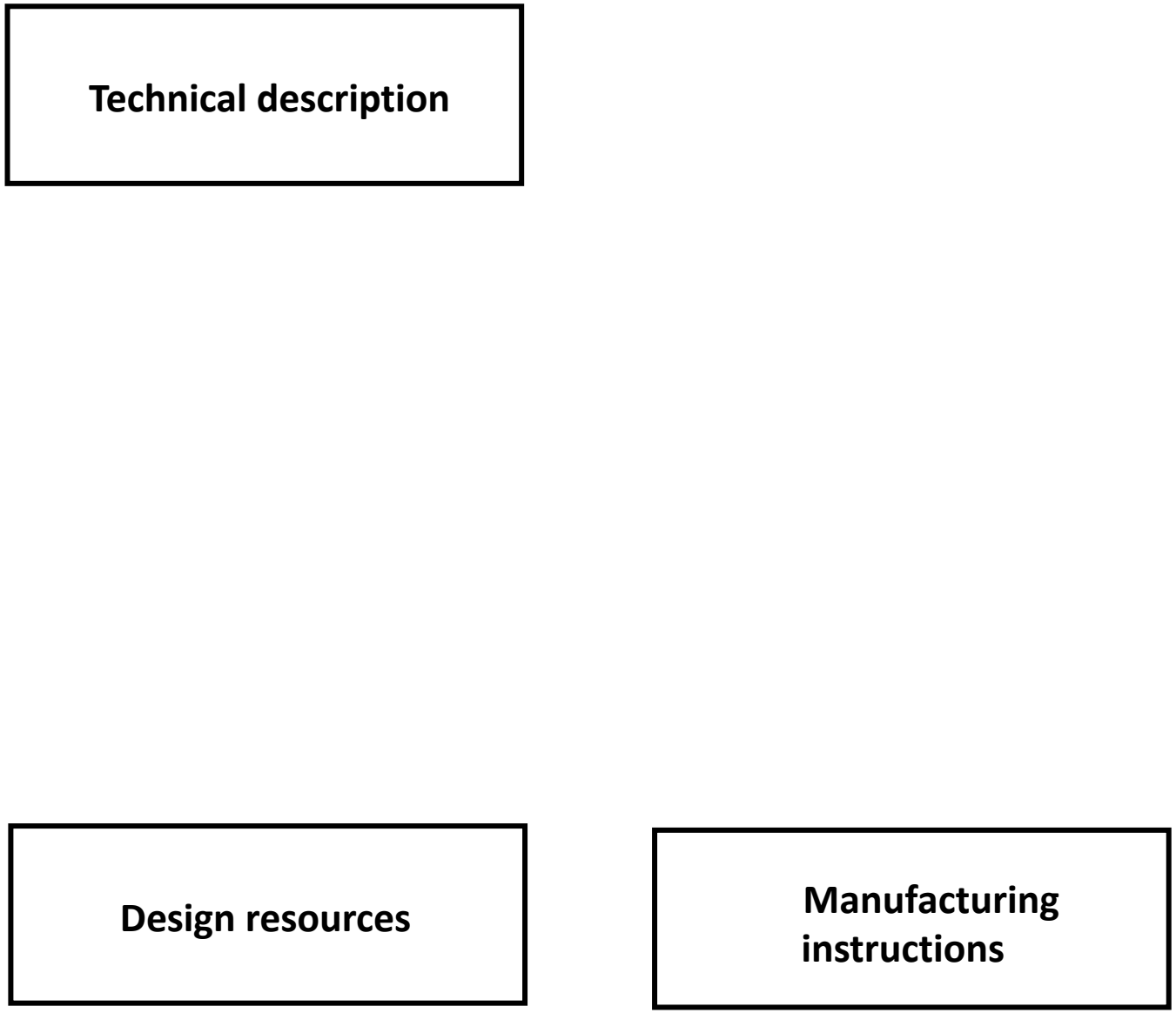
Separating *functions* and *function carriers*

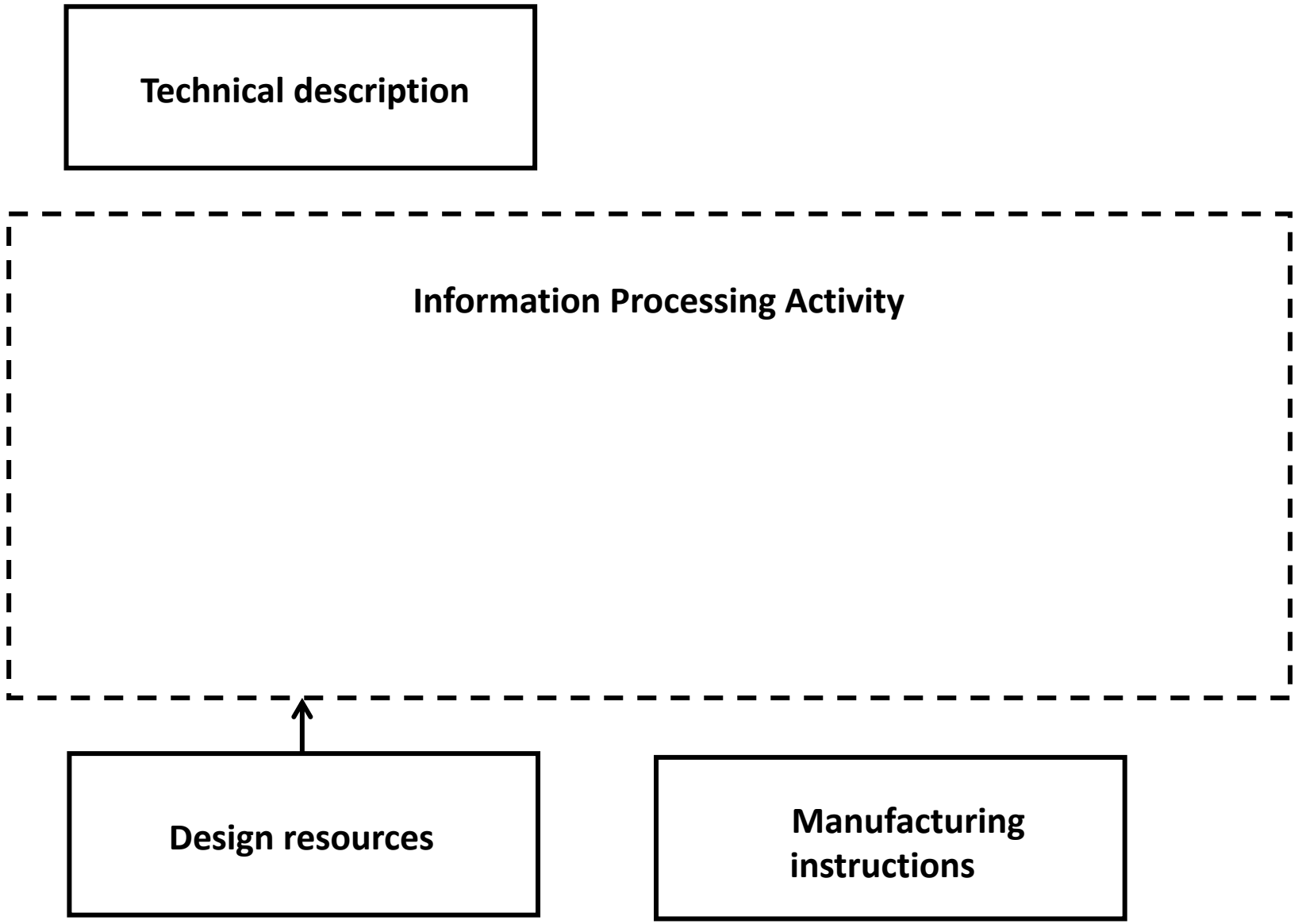
Functions and function carriers

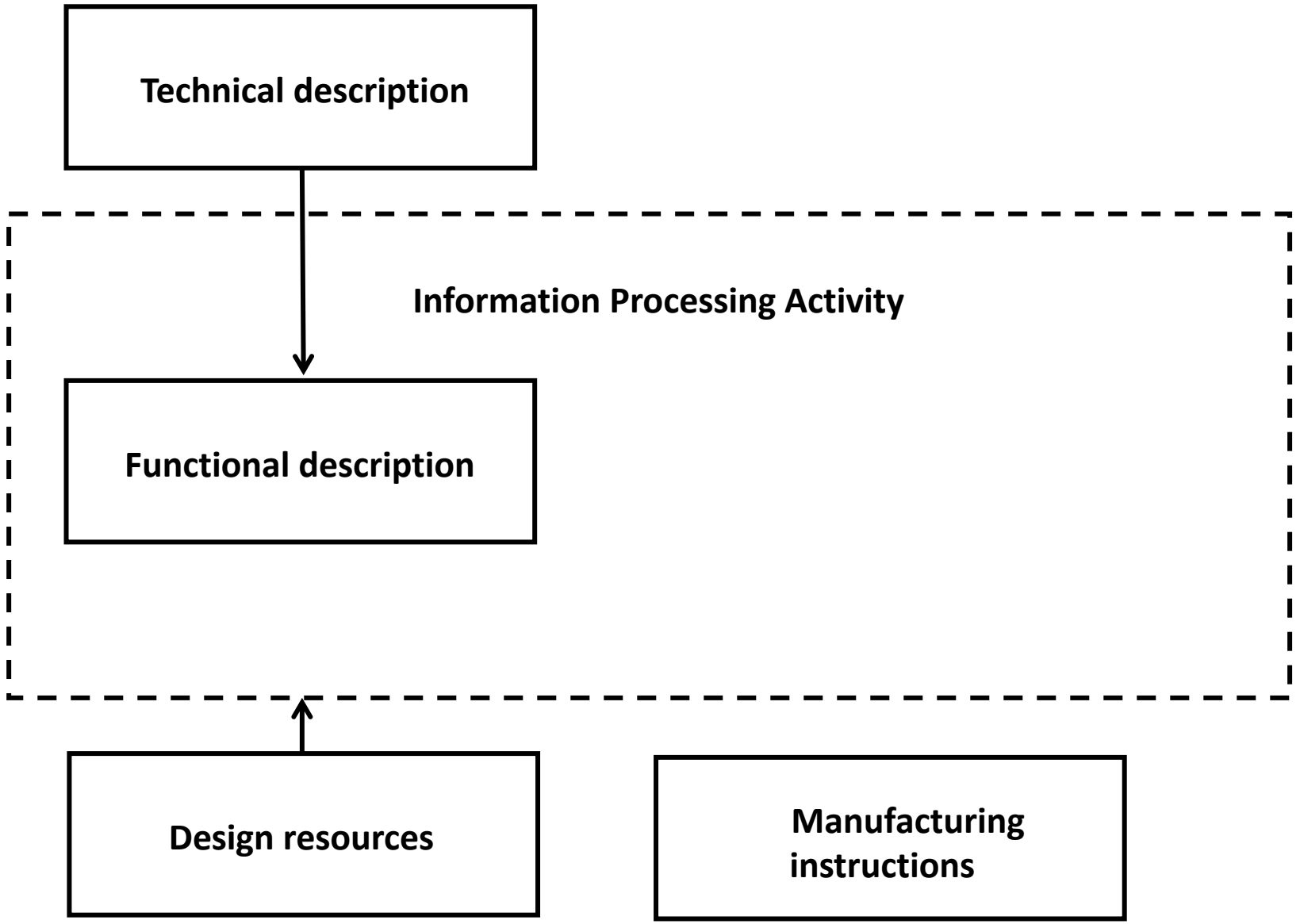
- A **function** is an abstraction of what we need to carry out
  - In other words, a function describes *what* a system needs to do

- A **function carrier** (sometimes called a *solution* or *solution* principle) is an *implementation* of a function
  - A function carrier describes *how* a function is carried out

- Example:
  - Supply Energy is a function and DC 5V Battery is a function carrier


Technical description
Design resources
Manufacturing instructions


Technical description
Information Processing Activity
Design resources
Manufacturing instructions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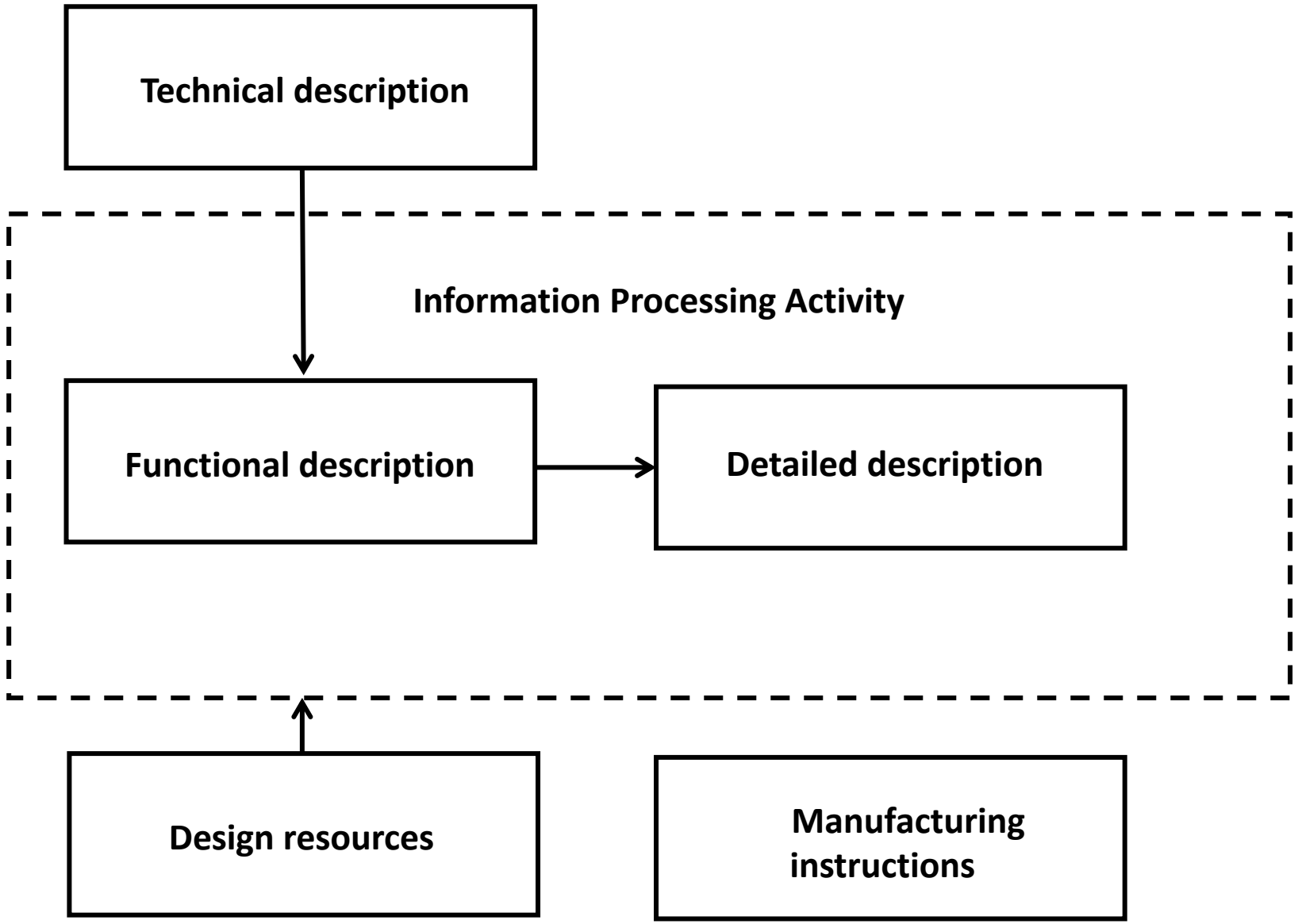
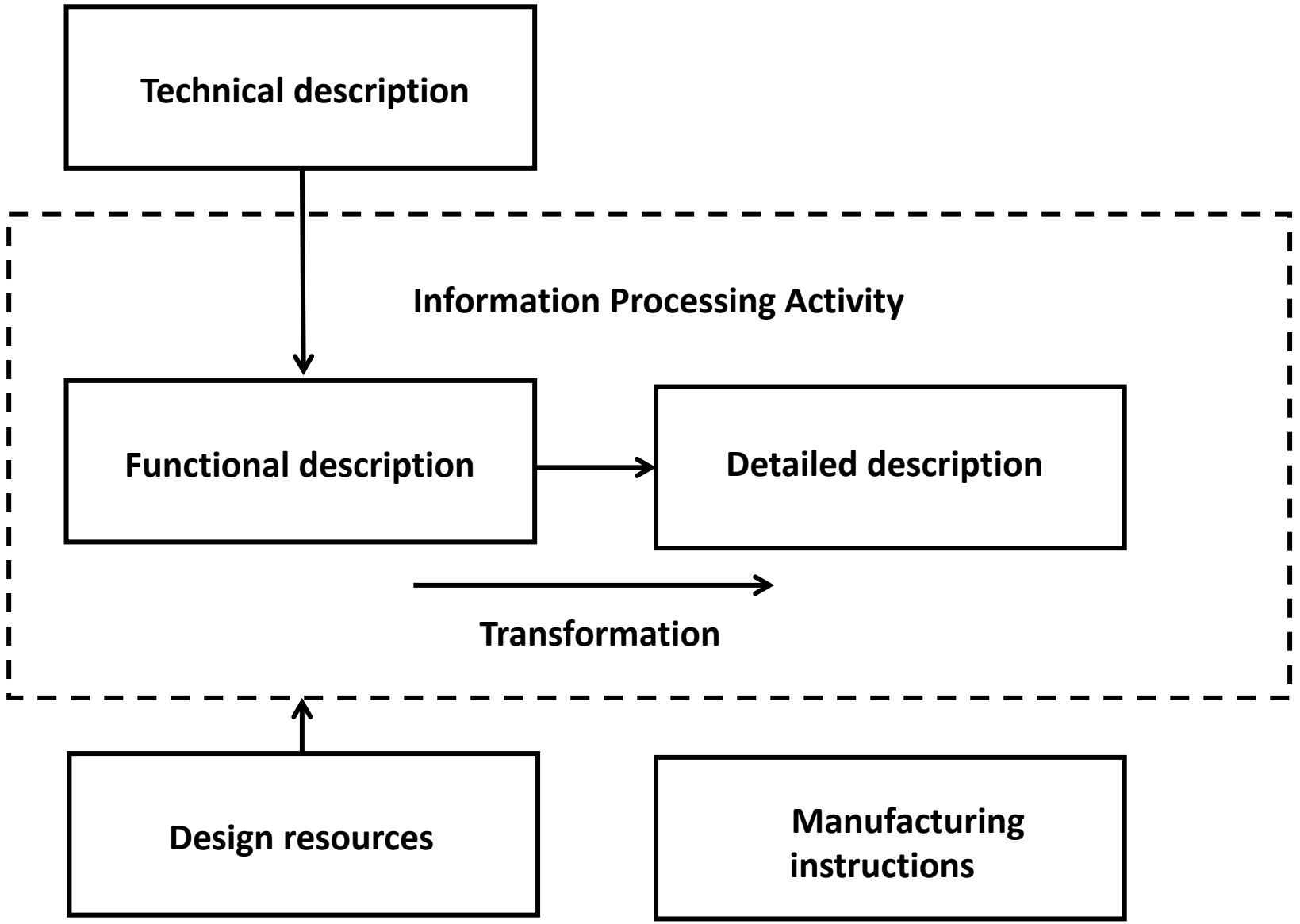
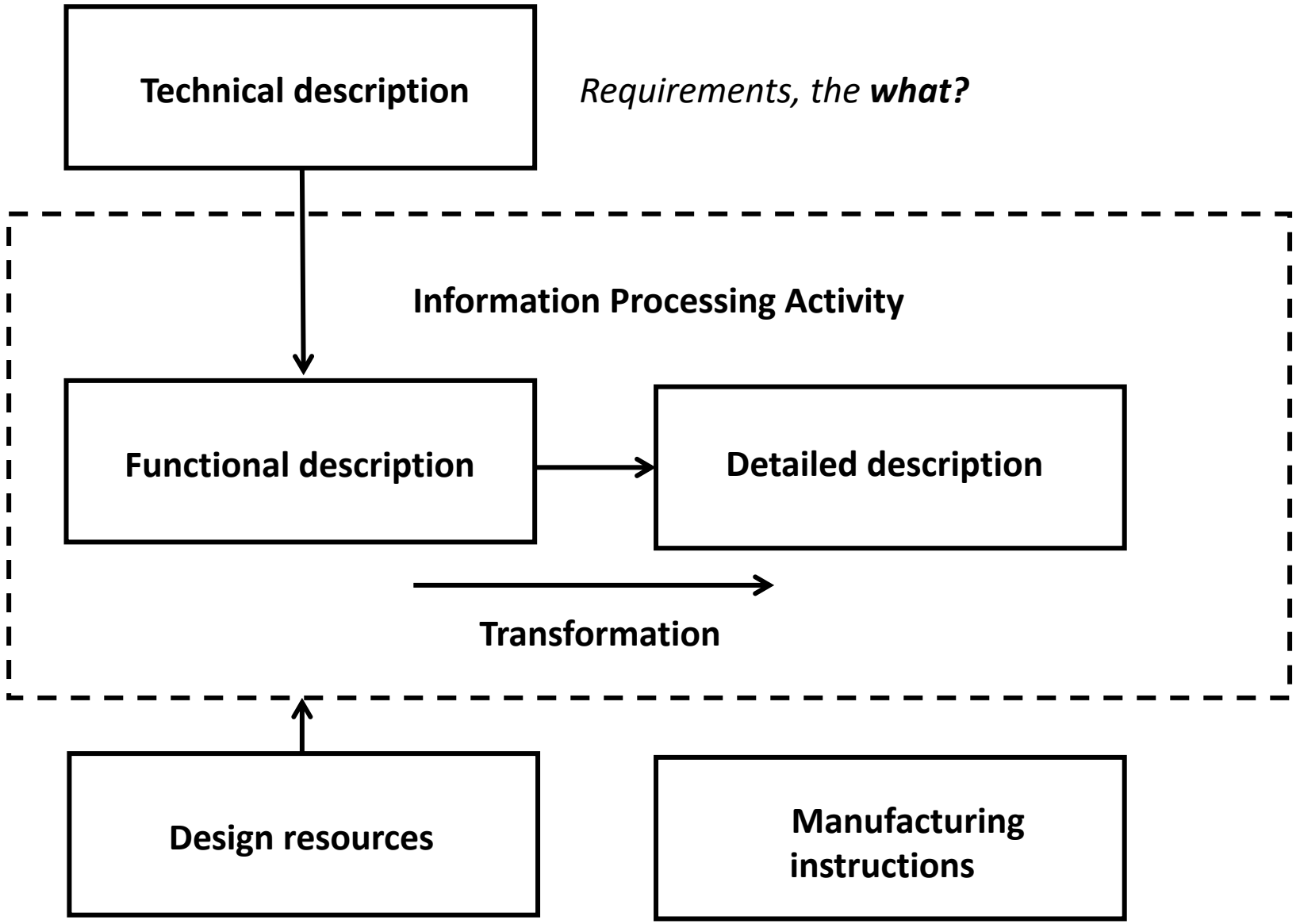
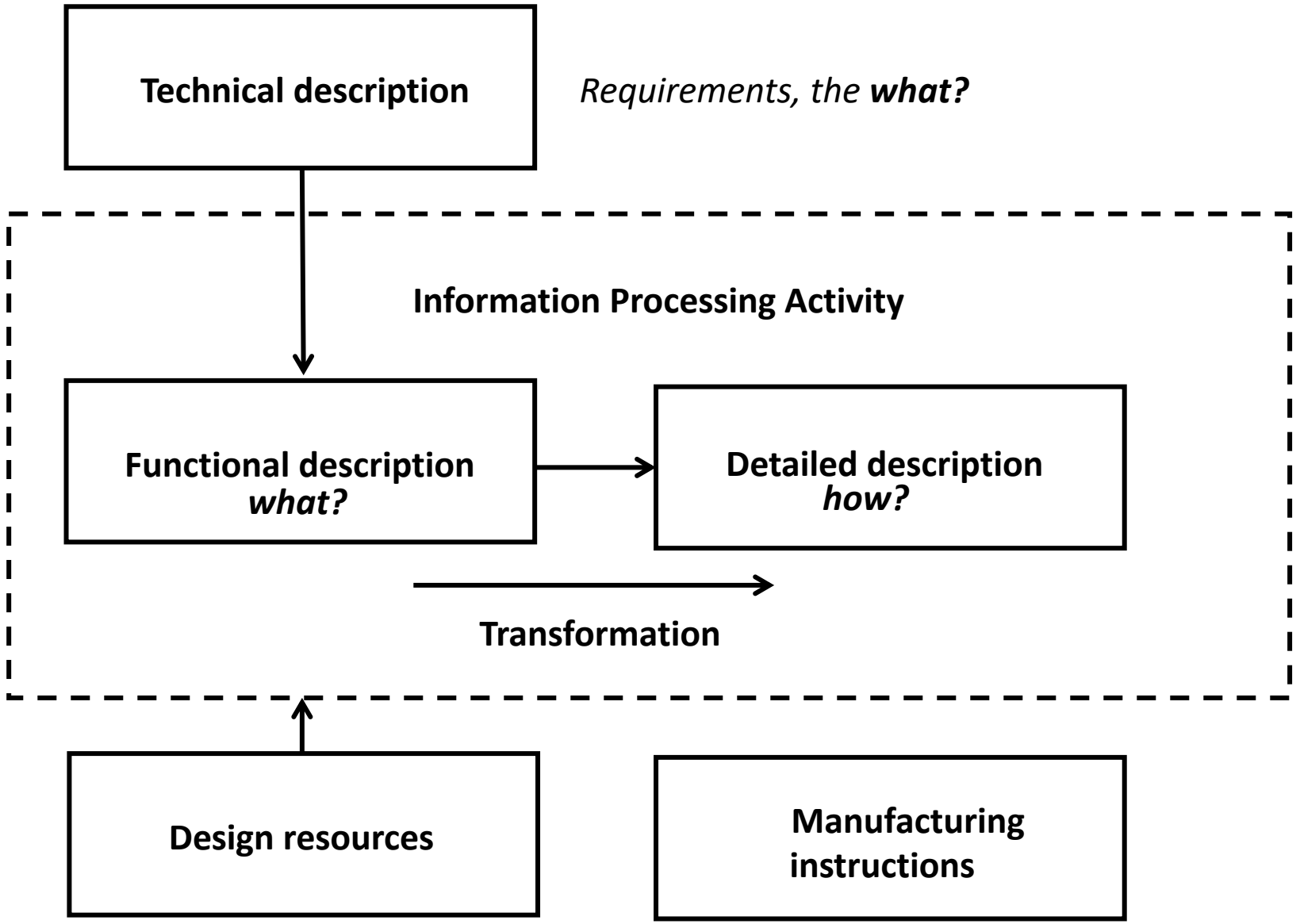
Information Processing Activity
Functional description
Design resources
Manufacturing instructions


Technical description
Information Processing Activity
Functional description
Detailed description
Design resources
Manufacturing instructions


Technical description
Information Processing Activity
Functional description
Detailed description
Transformation
Design resources
Manufacturing instructions


Technical description
Requirements, the what?
Information Processing Activity
Functional description
Detailed description
Transformation
Design resources
Manufacturing instructions


Technical description
Requirements, the what?
Information Processing Activity
Functional description
what?
Detailed description
how?
Transformation
Design resources
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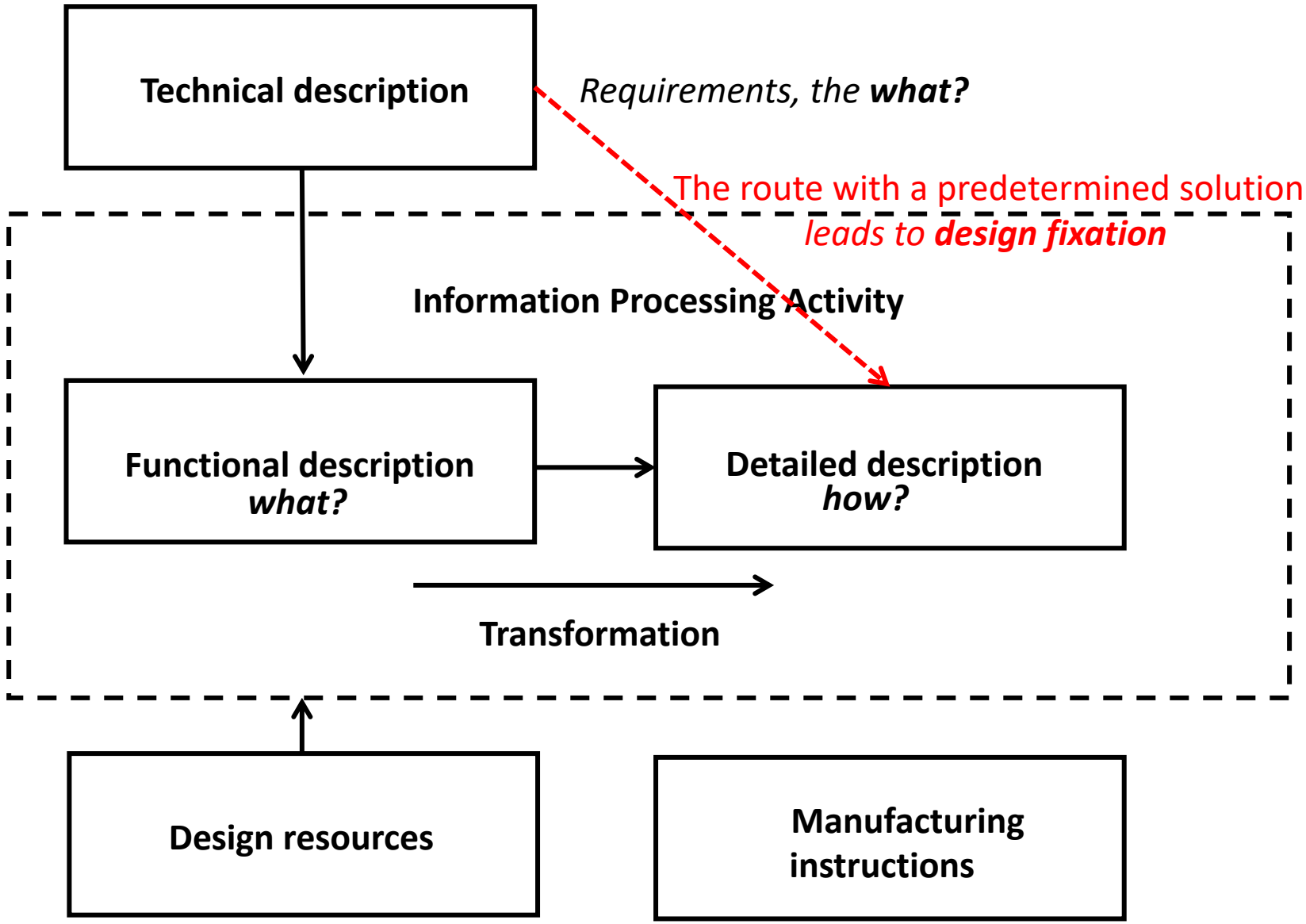
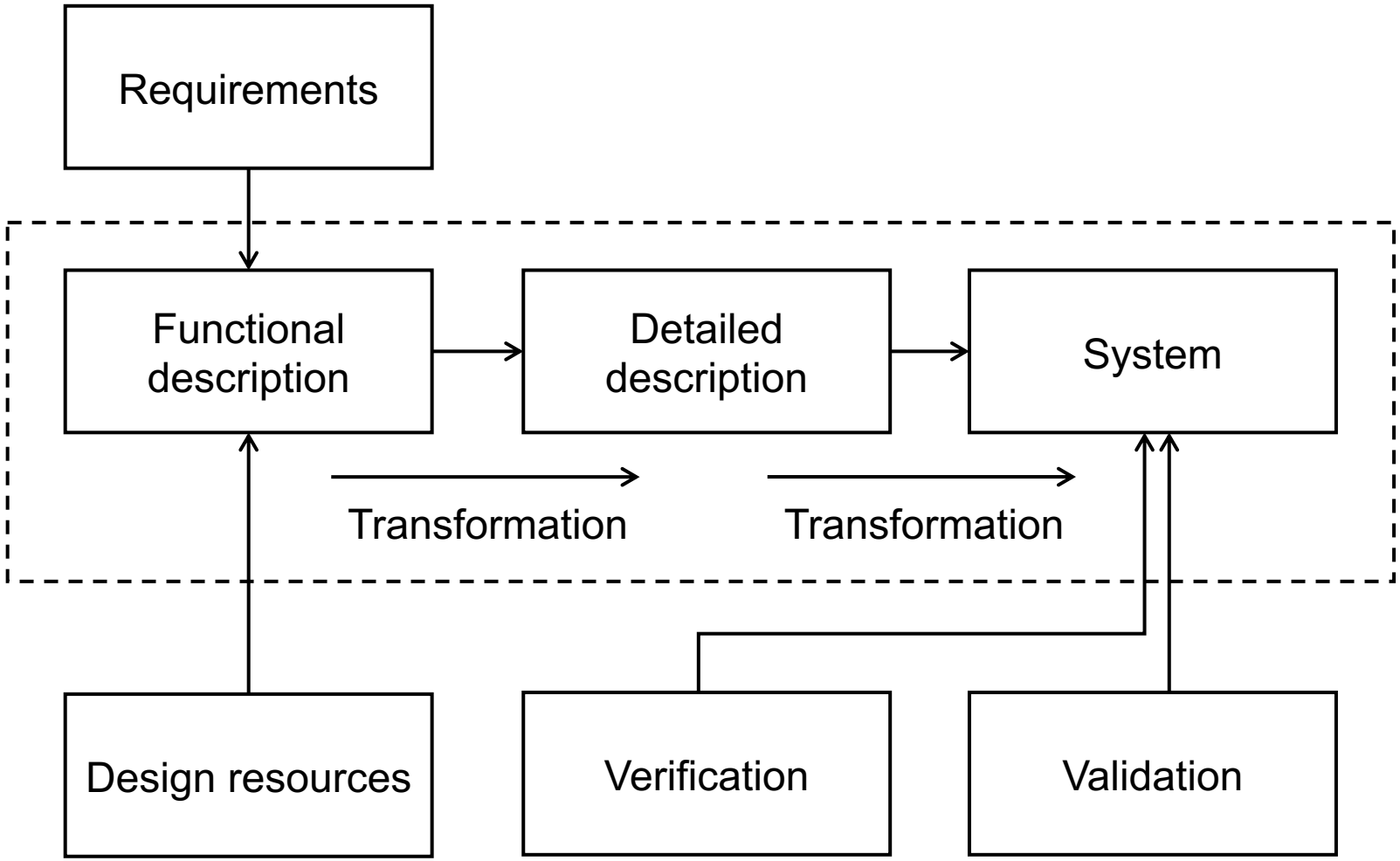
instructions


Technical description
Requirements, the what?
The route with a predetermined solution
leads to design fixation
Information Processing Activity
Functional description
what?
Detailed description
how?
Transformation
Design resources
Manufacturing
instructions

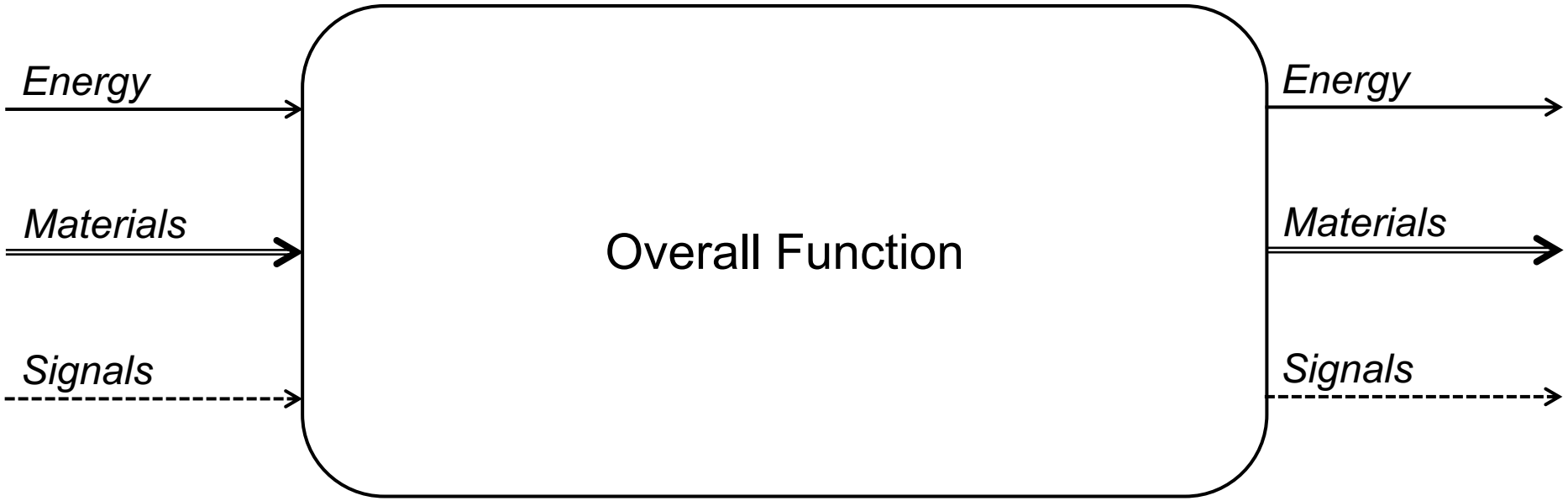
A modified model for intelligent interactive systems

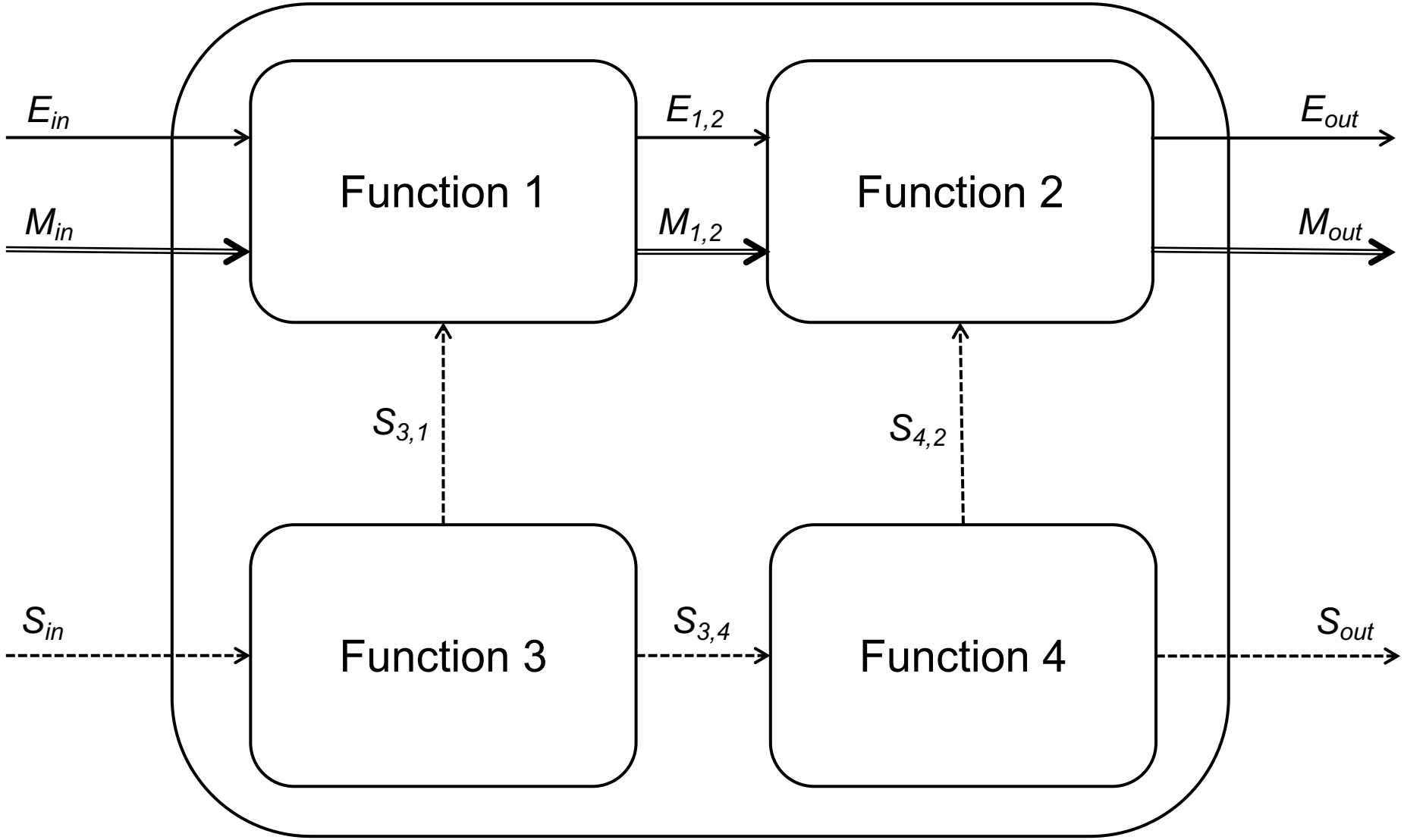


Kristensson, P.O. and Müllners, T. 2021. Design and analysis of intelligent text entry systems with function structure models and envelope analysis. In *Proceedings of the 39th ACM Conference on Human Factors in Computing Systems (CHI 2021)*. ACM Press: Article No. 584.

Decomposing *overall functions* to *function models*

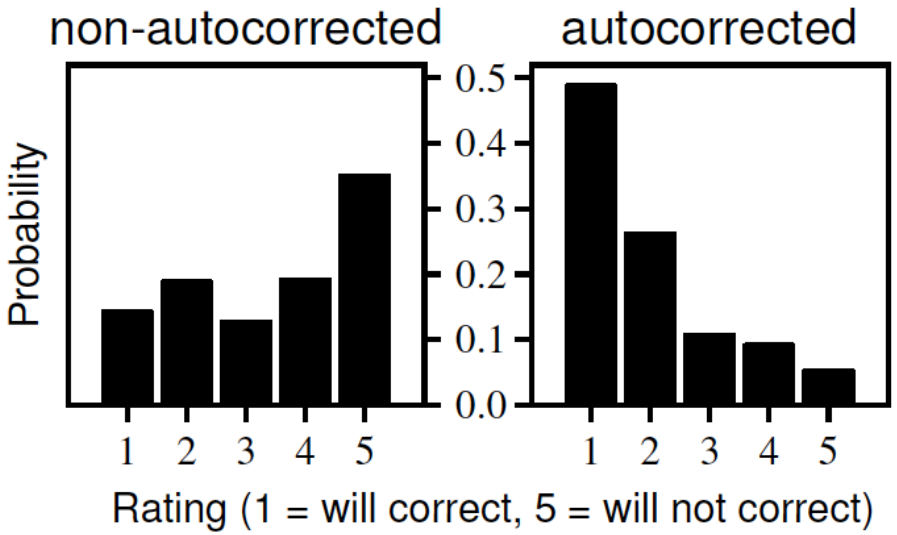
Overall function




E_{in}
M_{in}
S_{in}
Function 1
Function 2
Function 3
Function 4
$E_{1,2}$
$M_{1,2}$
$S_{3,1}$
$S_{4,2}$
$S_{3,4}$
E_{out}
M_{out}
S_{out}

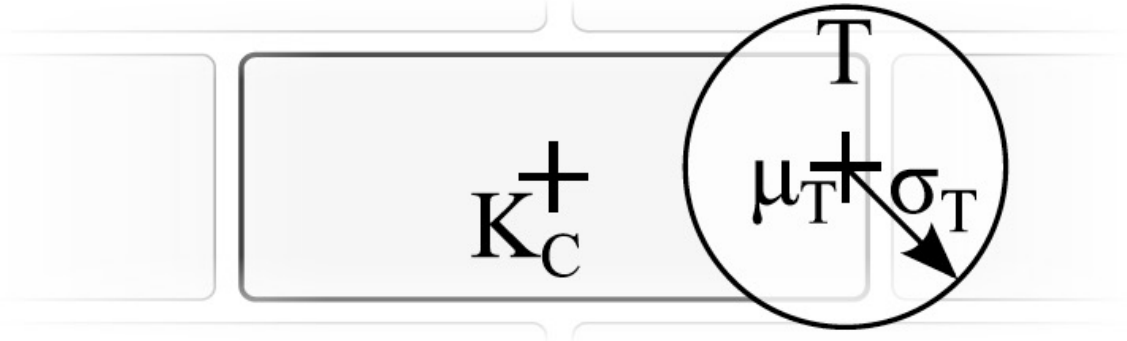
Example: the auto-correct trap

- Auto-correct is great when it works
- However, when auto-correct fails error correction activities exhibit a high penalty
- The solution is to provide users with more **agency** and allow them to regulate their **certainty**



Weir, D., Pohl, H., Rogers, S., Vertanen, K. and Kristensson, P.O. 2014. Uncertain text entry on mobile devices. In *Proceedings of the 32nd ACM Conference on Human Factors in Computing Systems (CHI 2014)*. ACM Press: 2307-2316.

Pressure-sensitive auto-correct



- Likelihood of a Gaussian with standard deviation regulated by pressure
- Standard deviation computed as C/ω_T, where C is a constant and ω_T is the pressure for touch T
- Tuned C so that the pressure of a typical touch had a standard deviation of half a key width

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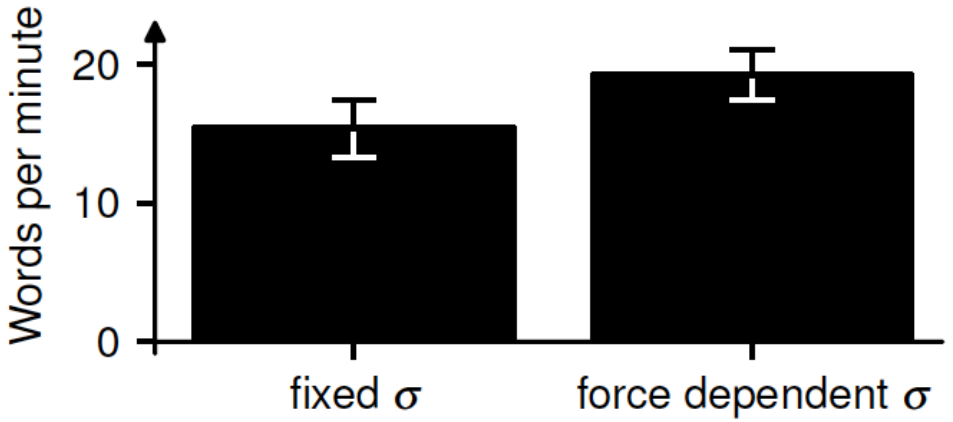
Results



- Enabling users to regulate their certainty by force resulted in a 10% percentage drop in active corrections (fixing a word by backspacing or retyping)
- This improved entry rate by 20%

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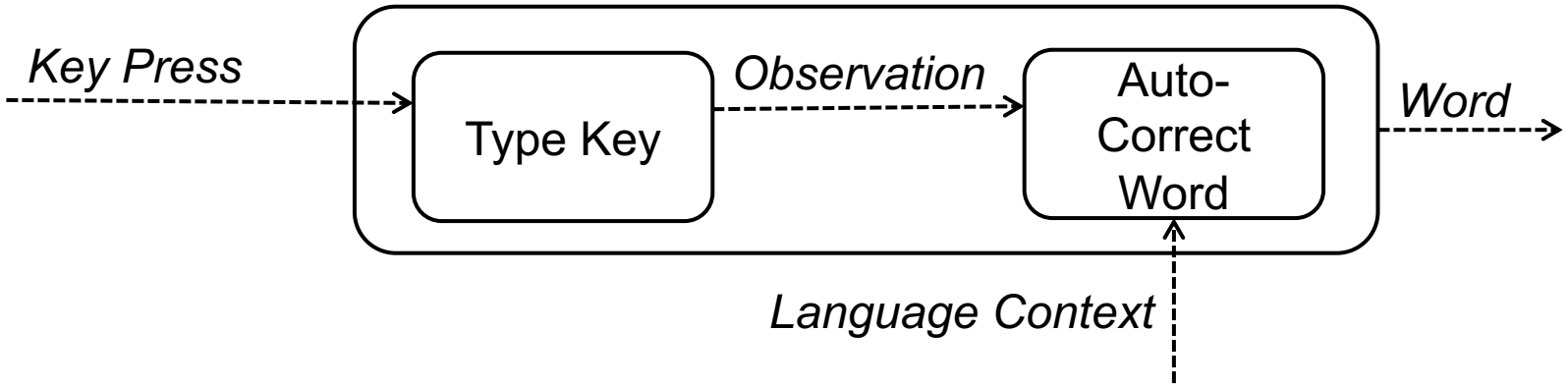
Overall function: auto-complete word



- Established auto-complete word function that receives a key press signal which is transduced to an observation signal
- The most likely word is auto-completed using an auto-correct word function and language model context

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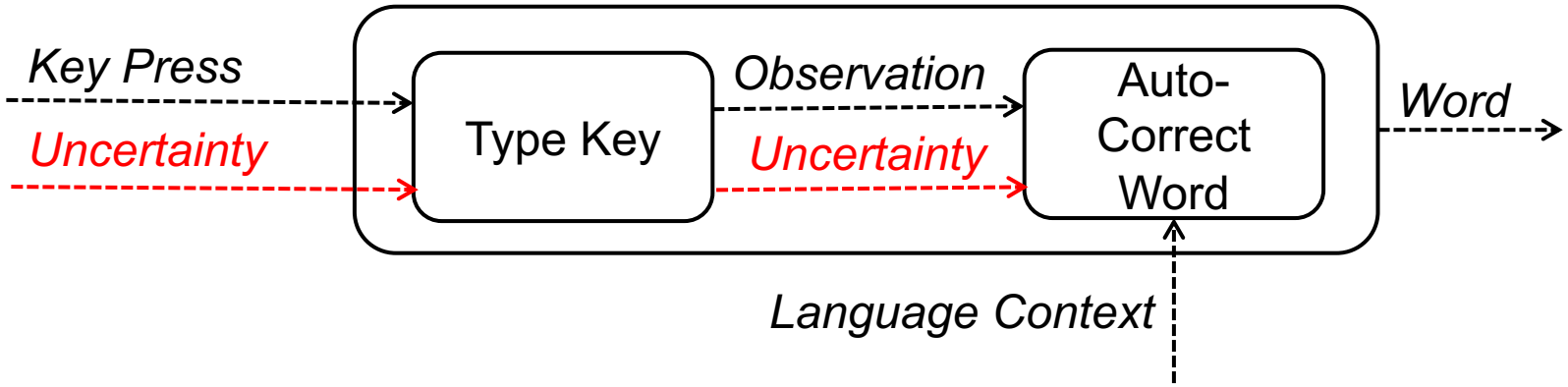
Overall function: regulate uncertainty



- Auto-correct function that allow users to regulate their uncertainty in their typing, for example, by pushing harder on keys they do not wish the system to auto-correct

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Parameterizing function models

Controllable and uncontrollable parameters

- Assessing **controllable parameters**
  - This provides us insight into parameters **we can govern**
  - Provides a basis for **design optimization**
- Assessing **uncontrollable parameters**
  - Parameters we have no direct influence over
  - Allows for **sensitivity analysis—**how sensitive are outcomes to parameter variations
- Both provide a basis for *informed* **requirements**

Carrying out *envelope analysis*

Design is a set of decisions

- Assume a multidimensional design space capturing all relevant concerns
- An **artefact** is a design instantiation in this space
- It is in fact an **operating point** in this multidimensional design space
- A design is rarely (if ever) **optimal**
- Setting the operating point necessitates making informed trade-off decisions
  - **Explicit trade-off decisions:** the designer understood the critical design dimensions and made **informed** decisions
  - **Implicit trade-off decisions:** the designer failed to understand and/or capture all critical design dimensions and one or several **uninformed** decisions resulted in an arbitrary design

Predicting the future

- **If** we have a functional description of a system

  and we have a parametrization of this functional description

  then we can *generate* outcomes using some form of *model*

- We fix some parameters and vary other parameters and effectively **move the operating point** of the design, thereby generate hypothetical design outcomes
- Such **envelope analysis** allows us to explore a range of design options *before* engaging in extensive user research
- Particularly critical for highly complex tightly coupled systems where A/B studies are merely studies of **a single operating point**

Why are word predictions typically not that useful?

Kristensson, P.O. and Müllners, T. 2021. Design and analysis of intelligent text entry systems with function structure models and envelope analysis. In *Proceedings of the 39th ACM Conference on Human Factors in Computing Systems (CHI 2021)*. ACM Press: Article No. 584.

Research question

- Large scale empirical data has demonstrated that, overall, word predictions do not seem to be useful for high-performance touchscreen text entry
- An A/B lab study found no significant difference in overall performance when using word prediction on the default Android system keyboard
- **What is the *mechanism* explaining the lack of observed benefit in using word prediction?**

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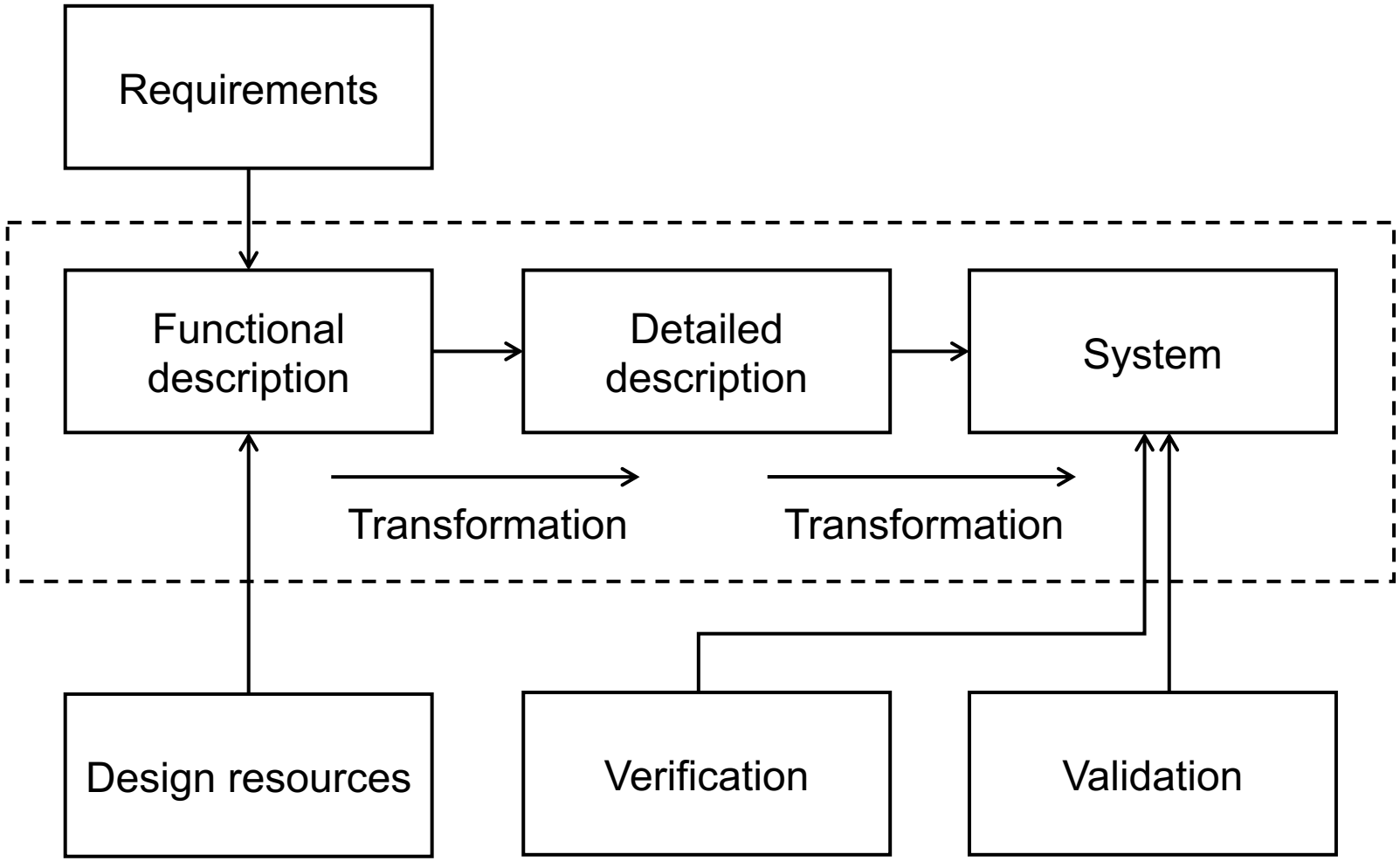
A modified model for intelligent interactive systems



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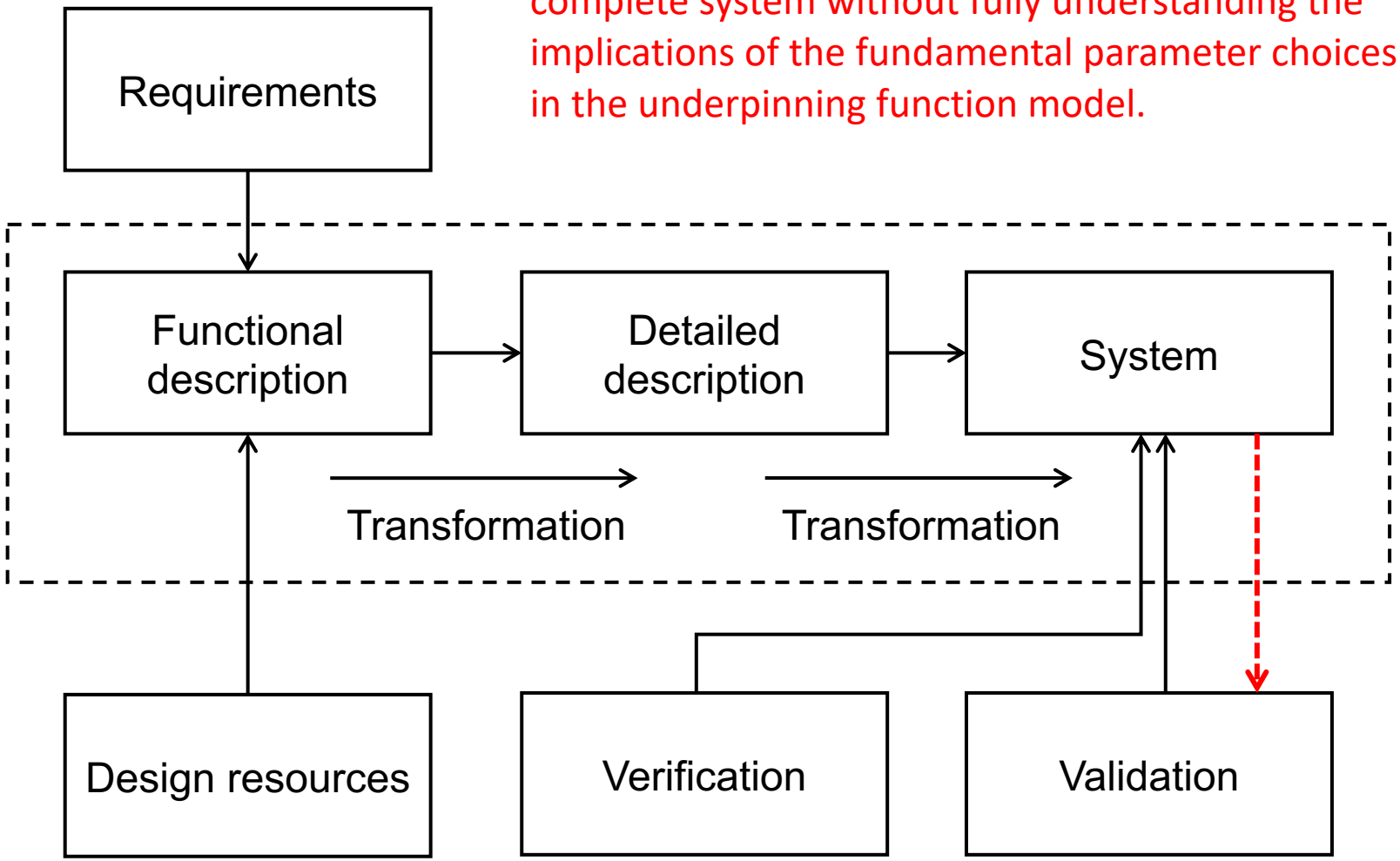
Short-circuit evaluation

Evaluating a particular design choice using a complete system without fully understanding the implications of the fundamental parameter choices in the underpinning function model.



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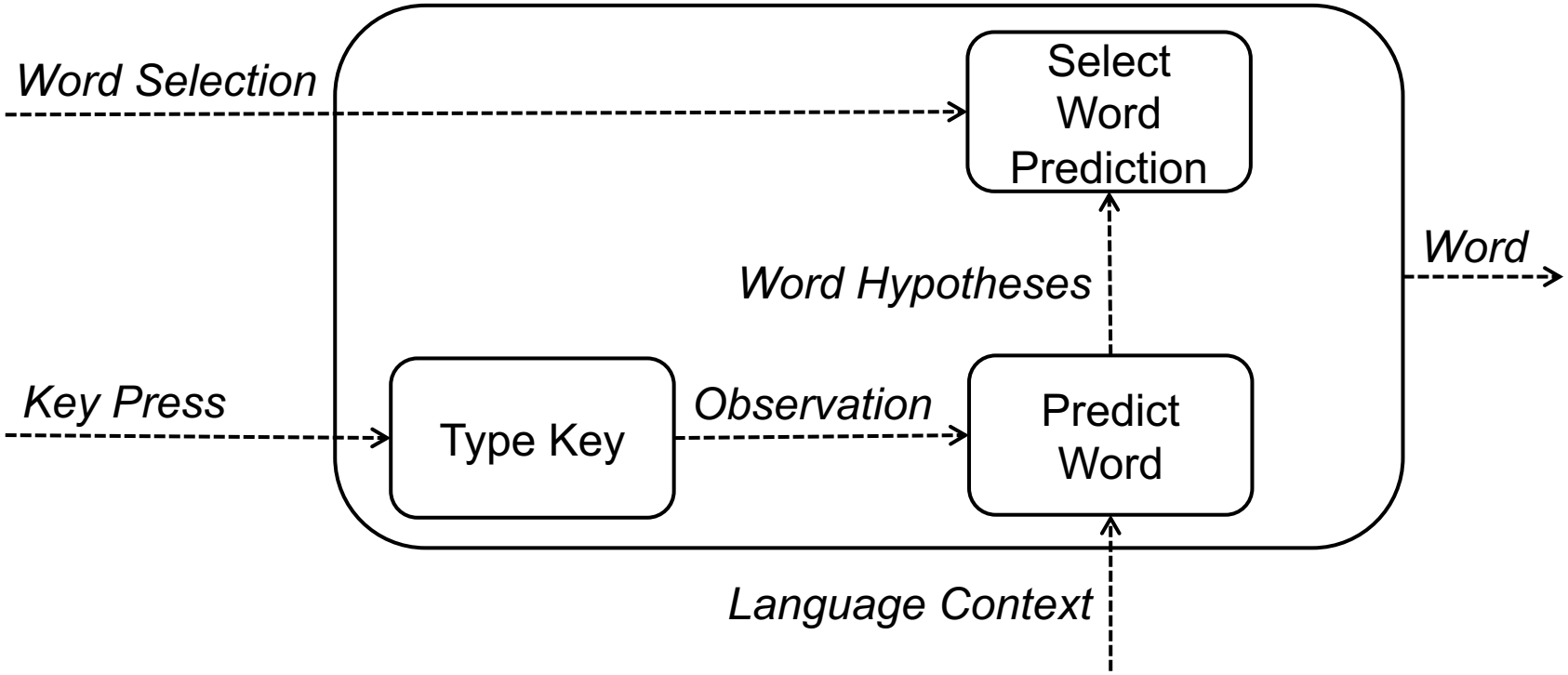
Overall function: predict word



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Function parameterization: word prediction

- We have two input signals and they can be parameterised as follows:
  - T_{key}: the time it takes the user to hit a key
  - T_{react}: the time it takes a user to react to a word prediction suggestion
- A latent set of parameters, *strategy*, generates process interaction between the design parameters:
  - L_{min}: restrict word prediction usage to words of a minimum length
  - k_{look}: type k keys then look
  - p_{max}: only attempt to check word predictions up to p_{max} key strokes per word
- Note that all these parameters are uncontrollable
- Other strategies are of course possible and in reality a user is likely using a mix of strategies

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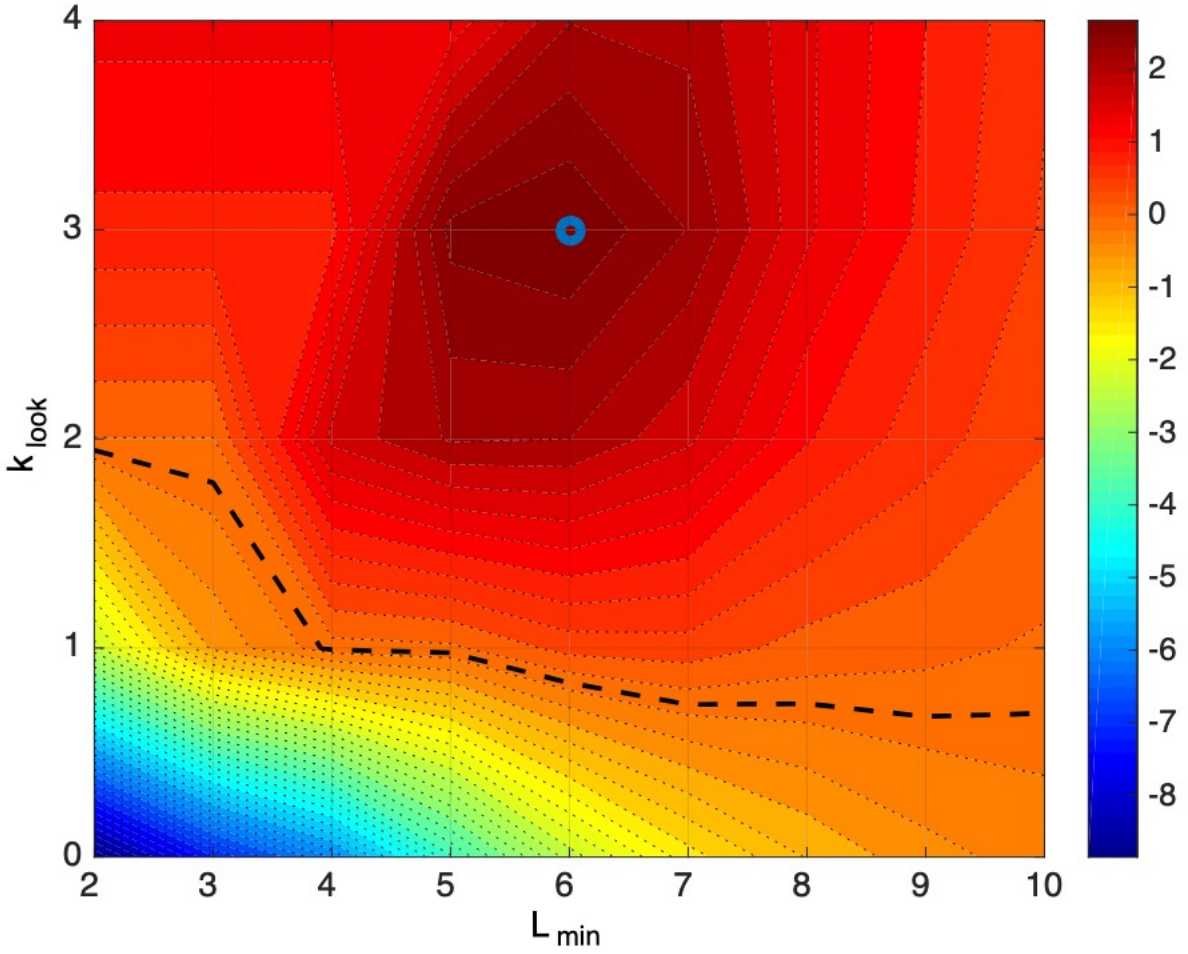
Envelope analysis

- Performance is strongly tied to the choice of typing strategy.
- The black dotted line is the zero-crossing and marks the boundary between performance gain and loss due to predictions.
- Any strategy that looks at word predictions without typing at least one letter is shown to slow the user down
- Performance gains are only realized if the user types at least the first two letters of each word before looking at predictions



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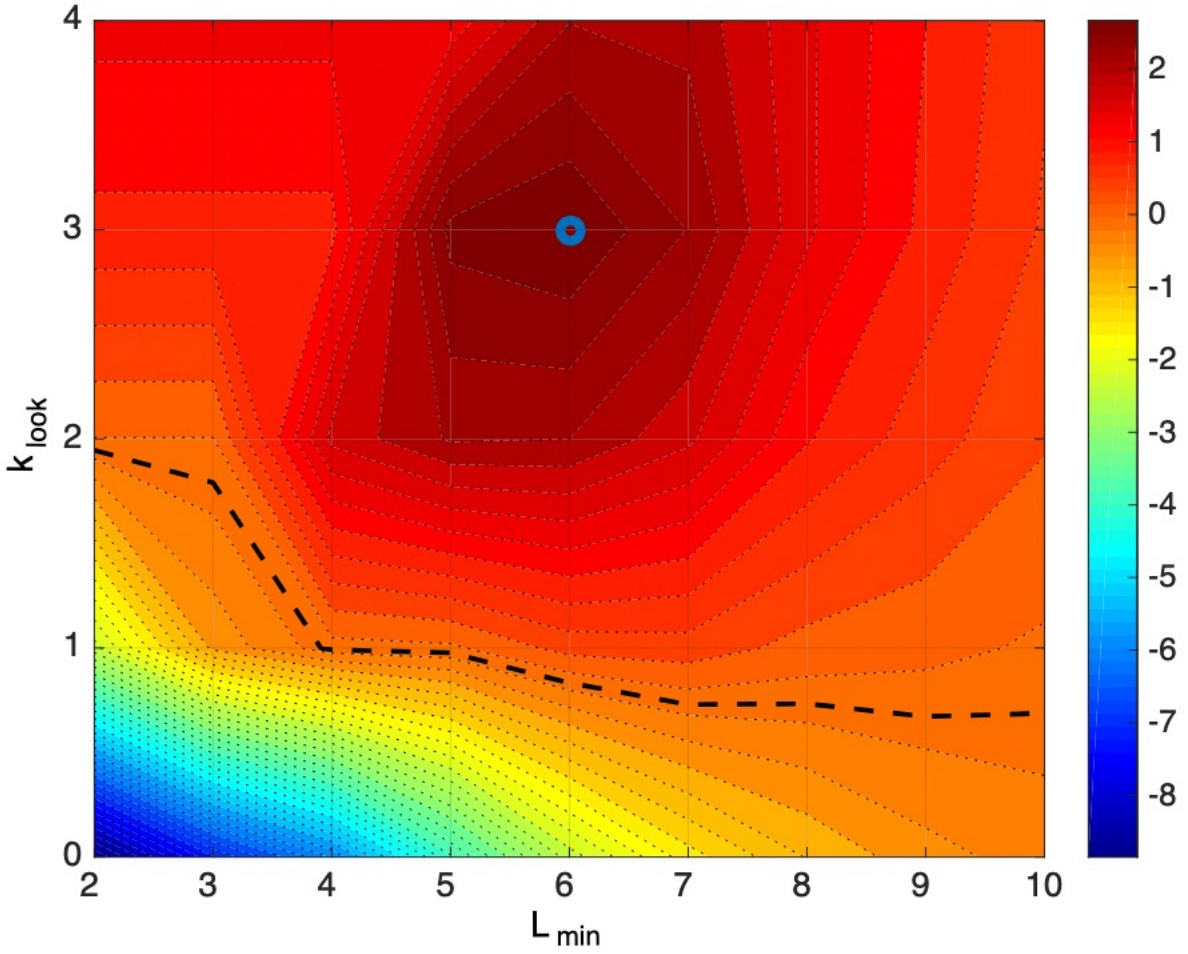
Envelope analysis

- The reliability of predictions increases with the number of letters typed
- Net entry rate can range from -8.8 to +2.9 words per minute solely as result of the choice of typing strategy
- The highest point identifies the optimal typing strategy: L_{min} = 6 ; k_{look} = 3



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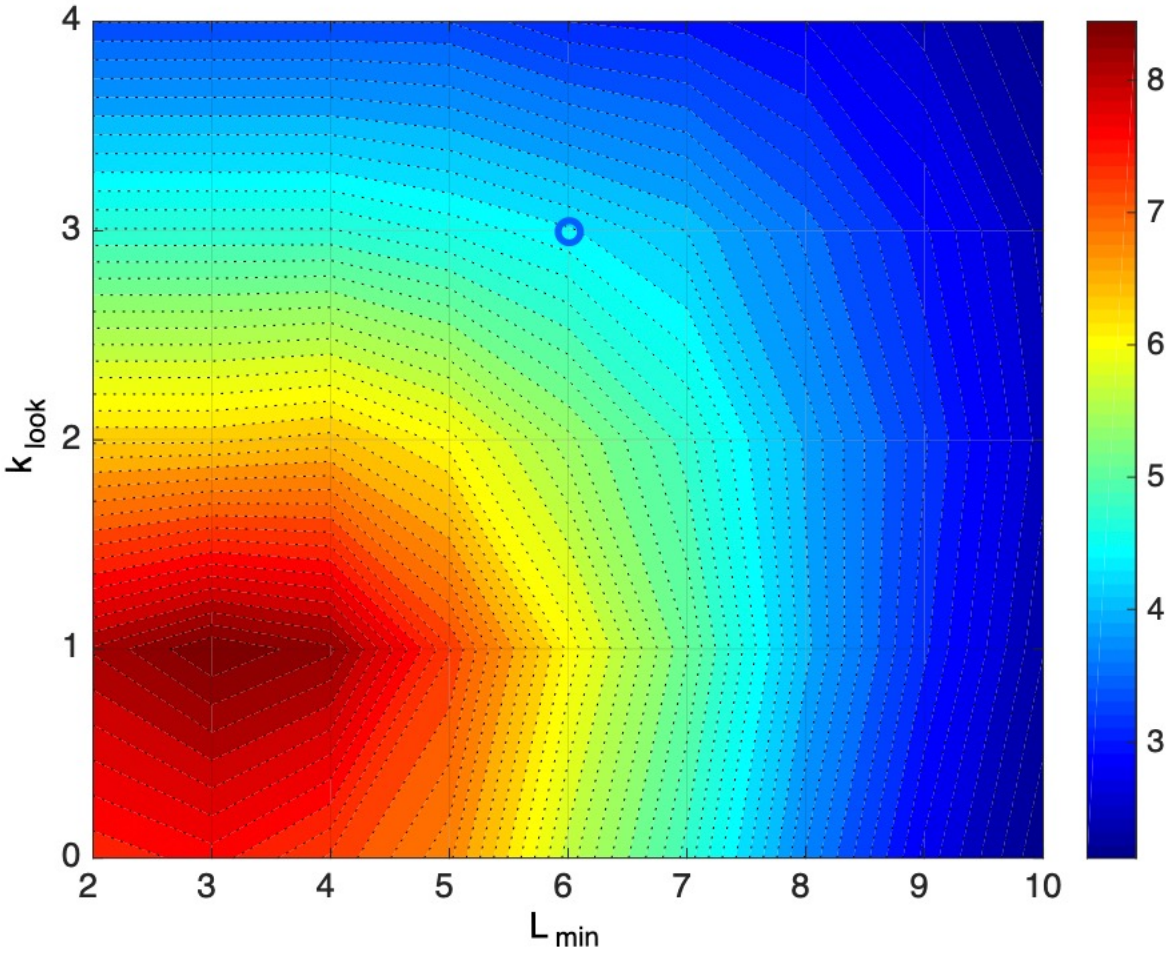
Envelope analysis

- Standard deviation of net entry rate is a measure of the uncertainty in using word prediction
- Typing strategies that make extensive use of word predictions (small L_{min} and k_{look}) have a higher standard deviation



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Sentence retrieval for nonspeaking individuals with motor disabilities

Kristensson, P.O., Lilley, J., Black, R. and Waller, A. 2020. A design engineering approach for quantitatively exploring context-aware sentence retrieval for nonspeaking individuals with motor disabilities. In *Proceedings of the 38th ACM Conference on Human Factors in Computing Systems (CHI 2020)*. ACM Press: Paper 398.

Research question

- Nonspeaking individuals with motor disabilities frequently communicate using augmentative and alternative communication (AAC) devices
- The typing rates are slow resulting in a *communication gap* between the AAC user and the speaking partner
- It has previously been observed that many AAC users reuse existing sentences by manually retrieving them
- **Can we provide complementary completion assistance by integrating context-aware sentence retrieval into an AAC user's typing workflow?**

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Sentence retrieval

Positive qualities

1. Potentially a very large increase in keystroke savings
2. Compatible with existing workflow (minimal learning)
3. Predictable outcomes for user allow for optimised retrieval after extensive use
4. Performance improves automatically the more it is used
5. Modular by its nature and allow for performance boosts by improving various sub-functions in the system

Negative qualities

1. Performance gains limited to sentence cache
2. Difficult to A/B evaluate system without expensive and invasive longitudinal study
3. Potential invasion of privacy
4. Many technical and non-technical design parameters and their individual and collective impact on eventual performance are unclear
5. As in all AAC design, representative data is extremely scarce

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Quantitative analysis: basic idea

- Use AAC surrogate set consisting of 5,000 **distinct** AAC sentences
- Draw 500, this forms the sentence cache
- Generate context tag families (such as **Location**) and context tags within context tags families (such as **Location1**, **Location2**, etc.)
- Simulate typing by creating a **typed sentence** that will contain:
    1. Context tags immediately assigned to the sentence (with assumptions on correct inference of context tags)
    2. Gradually build-up of words, either words completely typed out by simulated user, or auto-completed (with certain probability)
    3. Both context tags and generated words (either typed or auto-completed) are added to a bag-of-words
    4. The system uses this bag-of-words to rerank all sentences in the sentence cache
    5. A subset of top-ranked sentences (default: 4) are “shown” to the user
    6. If any of these match the intended sentence, there are observed keystroke savings

Kristensson, P.O., Lilley, J., Black, R. and Waller, A. 2020. A design engineering approach for quantitatively exploring context-aware sentence retrieval for nonspeaking individuals with motor disabilities. In *Proceedings of the 38th ACM Conference on Human Factors in Computing Systems (CHI 2020)*. ACM Press: Paper 398.

Quantitative analysis: setup

- Objective: Study emergent system performance envelope by varying controllable and uncontrollable parameters
- Implemented three standard information retrieval algorithms
  - IDF
  - BM25
  - Unigram
- The simplicity of the algorithms ensure the analysis is conservative

Kristensson, P.O., Lilley, J., Black, R. and Waller, A. 2020. A design engineering approach for quantitatively exploring context-aware sentence retrieval for nonspeaking individuals with motor disabilities. In *Proceedings of the 38th ACM Conference on Human Factors in Computing Systems (CHI 2020)*. ACM Press: Paper 398.

Quantitative analysis: main results

- Under very simple and conservative assumptions, context-aware sentence retrieval provides good gains in terms of keystroke savings
- Assuming two perfect context tags, we typically obtain a keystroke savings range of 94–97% when the word prediction accuracy is assumed to reside at around 80%
  - This forms an important requirement on this particular sub-system
- A context tagging error of 50% results in average keystroke savings at around 70%

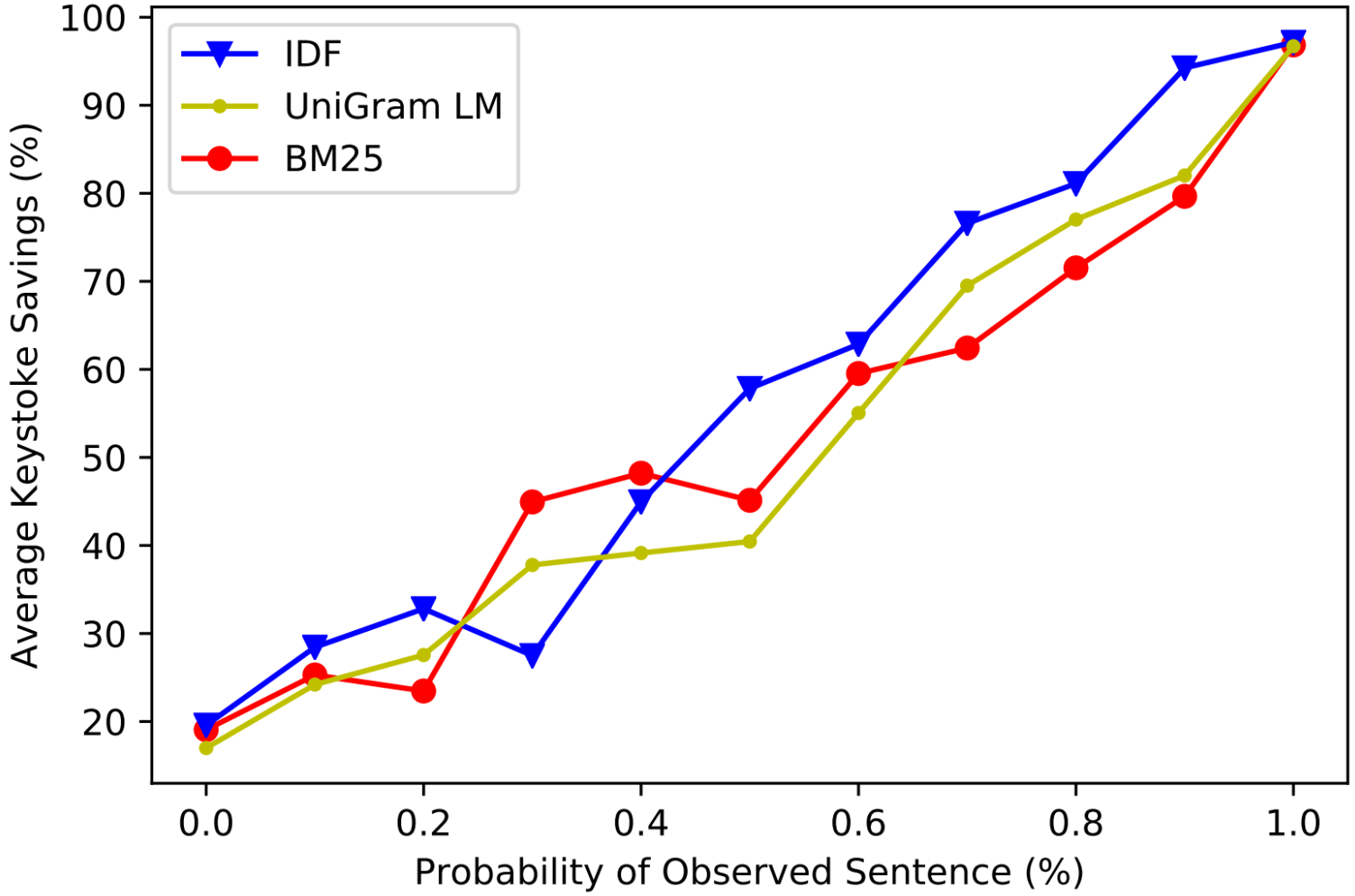
Kristensson, P.O., Lilley, J., Black, R. and Waller, A. 2020. A design engineering approach for quantitatively exploring context-aware sentence retrieval for nonspeaking individuals with motor disabilities. In *Proceedings of the 38th ACM Conference on Human Factors in Computing Systems (CHI 2020)*. ACM Press: Paper 398.

Quantitative analysis: design implications

- What does this mean:
  - For sentences **inside the cache**, context-aware sentence retrieval provides very large gains under even modest performance of context tagging and auto-complete
  - Auto-complete is not a major factor if context tagging is moderately accurate
  - The more context tags, the more accurate they are, and the more well-distributed they are across sentences, the better the performance
  - More sentences help…

Kristensson, P.O., Lilley, J., Black, R. and Waller, A. 2020. A design engineering approach for quantitatively exploring context-aware sentence retrieval for nonspeaking individuals with motor disabilities. In *Proceedings of the 38th ACM Conference on Human Factors in Computing Systems (CHI 2020)*. ACM Press: Paper 398.

Sentence outside cache, worst-case analysis



Kristensson, P.O., Lilley, J., Black, R. and Waller, A. 2020. A design engineering approach for quantitatively exploring context-aware sentence retrieval for nonspeaking individuals with motor disabilities. In *Proceedings of the 38th ACM Conference on Human Factors in Computing Systems (CHI 2020)*. ACM Press: Paper 398.

Can we generate sentences for nonspeaking individuals with motor disabilities?

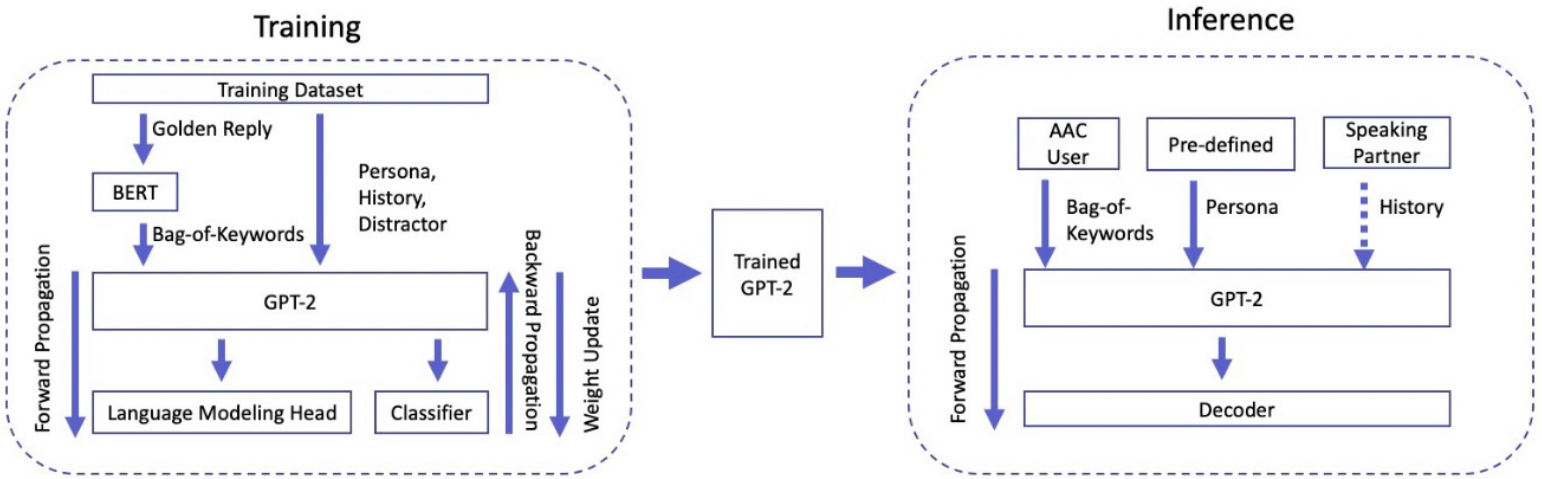
Shen, S., Yang, B., Dudley, J.J. and Kristensson, P.O. 2022. KWickChat: a multi-turn dialogue system for AAC using context-aware sentence generation by bag-of-keywords. In *Proceedings of the 27th ACM International Conference on Intelligent User Interfaces (IUI 2022)*. ACM Press: 853-867.

Research question

- Sentence retrieval works but is obviously limited to sentence reuse
- **Can we allow AAC users to *prompt* a sentence generation system to output sentences that are meaningful and relevant?**

Shen, S., Yang, B., Dudley, J.J. and Kristensson, P.O. 2022. KWickChat: a multi-turn dialogue system for AAC using context-aware sentence generation by bag-of-keywords. In *Proceedings of the 27th ACM International Conference on Intelligent User Interfaces (IUI 2022)*. ACM Press: 853-867.

Approach: KWickChat



- Use GPT (GPT-2) to generate sentences
- Prompt sentence generation using three sources:
  - **Keywords:** keywords typed by the user
  - **History:** prior sentences in the dialogue
  - **Personas:** tags/sentences describing the user

Shen, S., Yang, B., Dudley, J.J. and Kristensson, P.O. 2022. KWickChat: a multi-turn dialogue system for AAC using context-aware sentence generation by bag-of-keywords. In *Proceedings of the 27th ACM International Conference on Intelligent User Interfaces (IUI 2022)*. ACM Press: 853-867.

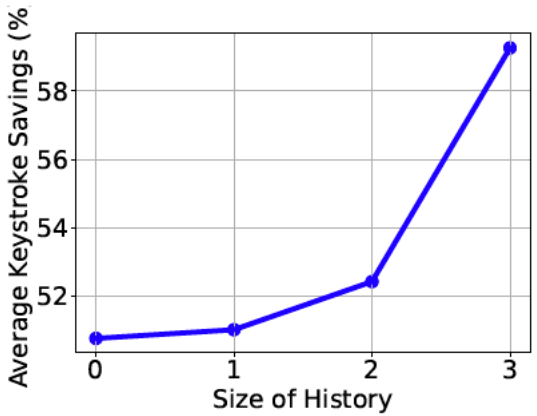
Example conversation

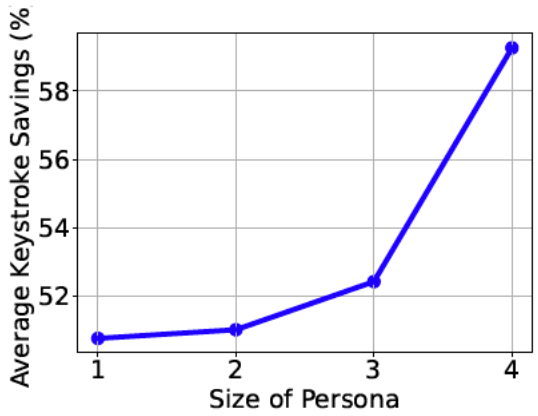
Persona 1	Persona 2
I like to ski	I am an artist
My wife does not like me anymore	I have four children
I have went to Mexico 4 times this year	I recently got a cat
I hate Mexican food	I enjoy walking for exercise
I like to eat cheetos	I love watching Games of Thrones

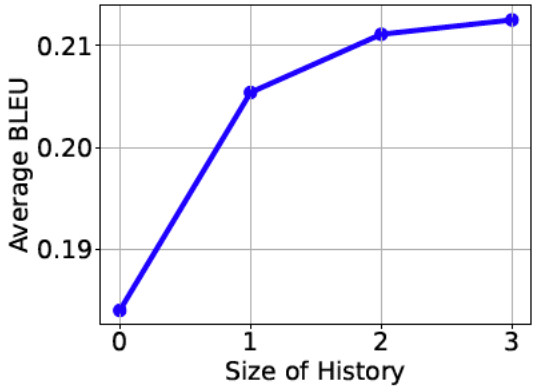
PERSON 1:	Hi
PERSON 2:	Hello ! How are you today ?
PERSON 1:	I am good thank you, how are you
PERSON 2:	Great, thanks! My children and I were just about to watch Games of Thrones.
PERSON 1:	Nice ! How old are your children?
PERSON 2:	I have four that range in age from 10 to 21. You?
PERSON 1:	I do not have children at the moment.
PERSON 2:	That just means you get to keep all the popcorn for yourself.
PERSON 1:	And Cheetos at the moment!
PERSON 2:	Good choice. Do you watch Game of Thrones?
PERSON 1:	No, I do not have much time for TV.
PERSON 2:	I usually spend my time painting: but, I love the show.

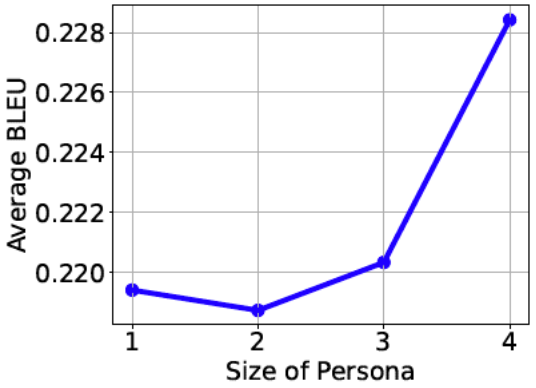
Shen, S., Yang, B., Dudley, J.J. and Kristensson, P.O. 2022. KWickChat: a multi-turn dialogue system for AAC using context-aware sentence generation by bag-of-keywords. In *Proceedings of the 27th ACM International Conference on Intelligent User Interfaces (IUI 2022)*. ACM Press: 853-867.

Envelope analysis





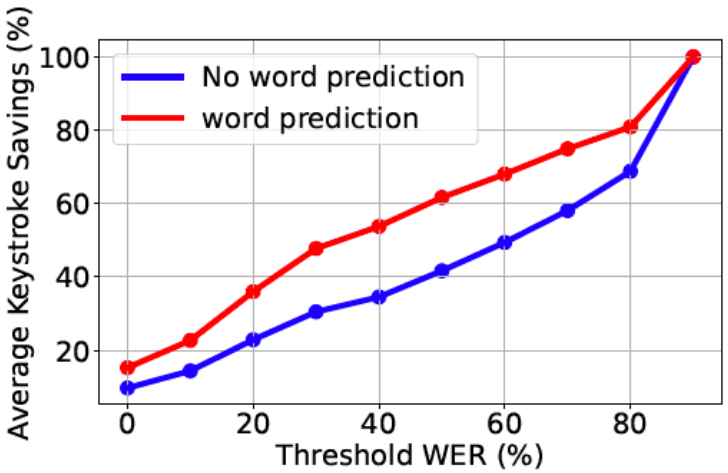


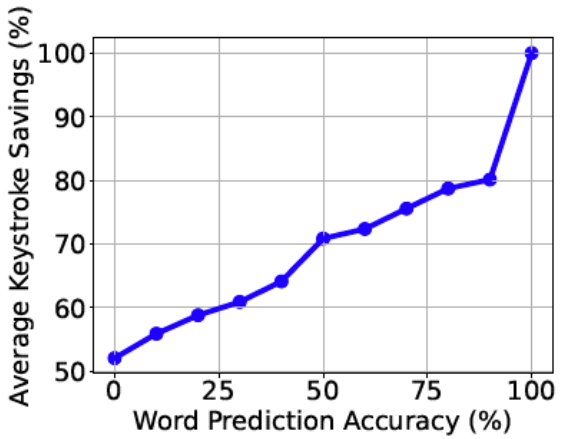


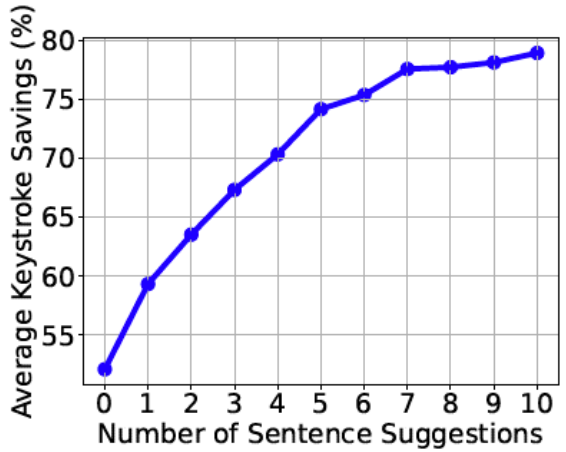
- Estimating benefits of persona (tags describing the user) and history (prior exchanges in a dialogue)
- Allows estimation of benefits and determination of design parameters without elaborate user studies (which in this case are also very difficult to carry out)

Shen, S., Yang, B., Dudley, J.J. and Kristensson, P.O. 2022. KWickChat: a multi-turn dialogue system for AAC using context-aware sentence generation by bag-of-keywords. In *Proceedings of the 27th ACM International Conference on Intelligent User Interfaces (IUI 2022)*. ACM Press: 853-867.

Envelope analysis







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Shen, S., Yang, B., Dudley, J.J. and Kristensson, P.O. 2022. KWickChat: a multi-turn dialogue system for AAC using context-aware sentence generation by bag-of-keywords. In *Proceedings of the 27th ACM International Conference on Intelligent User Interfaces (IUI 2022)*. ACM Press: 853-867.

Summary

- Establish *system boundaries*
  - Decide what the overall *concerns* of the system are
- Separate *functions* and *function carriers*
  - Focus on *what* needs to be done rather than *how* to do it
- Decompose *overall functions* into *function models*
  - Establish *relationships* between functions before considering solutions
- *Parameterize* function models
  - Attach *controllable* and *uncontrollable* parameters to a design at a functional level
- Carry out *envelope analyses*
  - Generate hypothetical *operating points* to understand the *mechanisms* underpinning estimated performance as a function of the parameters

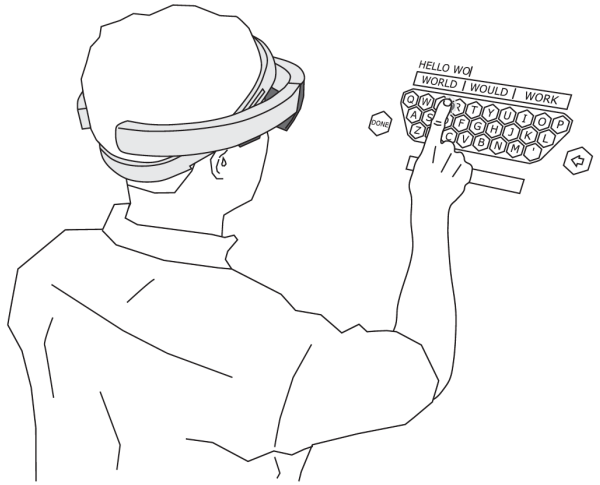
Key papers

- Kristensson, P.O., Lilley, J., Black, R. and Waller, A. 2020. A design engineering approach for quantitatively exploring context-aware sentence retrieval for nonspeaking individuals with motor disabilities. In *Proceedings of the 38th ACM Conference on Human Factors in Computing Systems (CHI 2020)*. ACM Press: Paper 398.
- Kristensson, P.O. and Müllners, T. 2021. Design and analysis of intelligent text entry systems with function structure models and envelope analysis. In *Proceedings of the 39th ACM Conference on Human Factors in Computing Systems (CHI 2021)*. ACM Press: Article No. 584.
- Shen, S., Yang, B., Dudley, J.J. and Kristensson, P.O. 2022. KWickChat: a multi-turn dialogue system for AAC using context-aware sentence generation by bag-of-keywords. In *Proceedings of the 27th ACM International Conference on Intelligent User Interfaces (IUI 2022)*. ACM Press: 853-867.
- Kristensson, P.O. , Mjelde, M. and Vertanen, K. 2023. Understanding adoption barriers to dwell-free eye-typing: design implications from a qualitative deployment study and computational simulations. In *Proceedings of the 28th ACM International Conference on Intelligent User Interfaces (IUI 2023)*. ACM Press: 607-620.

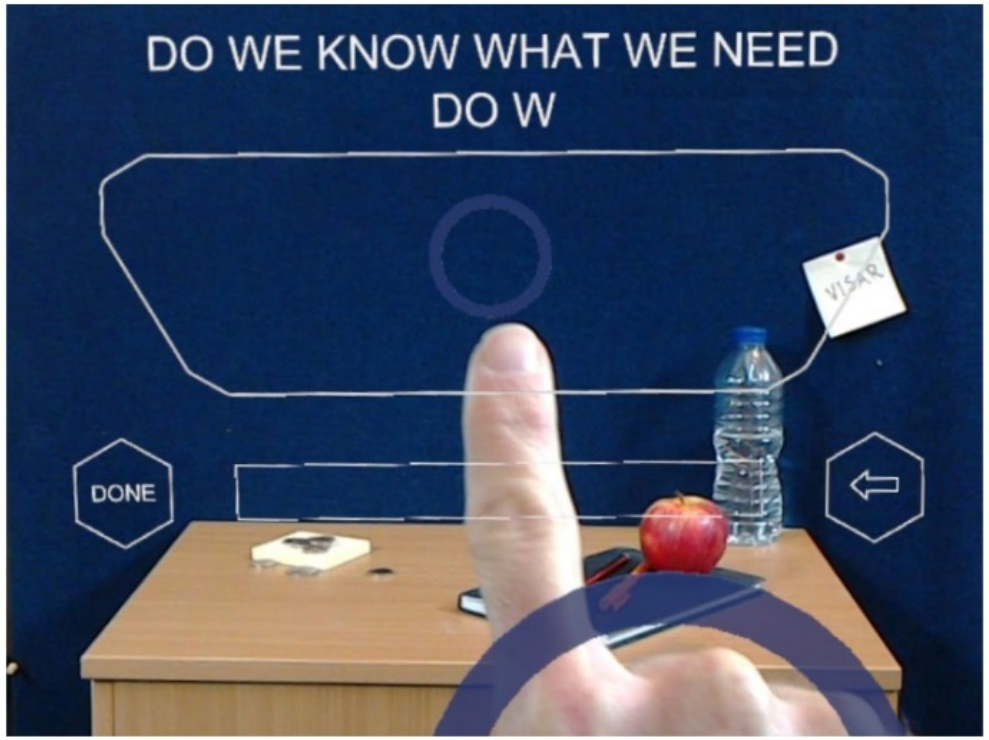
Statistical Keyboard Decoding
Motivating Examples

Hand tracked text entry in thin air

1. Lack of sophisticated models informed by user behaviour
2. Lack of suitable training data
3. Systems need to translate uncertain observations of user input into text

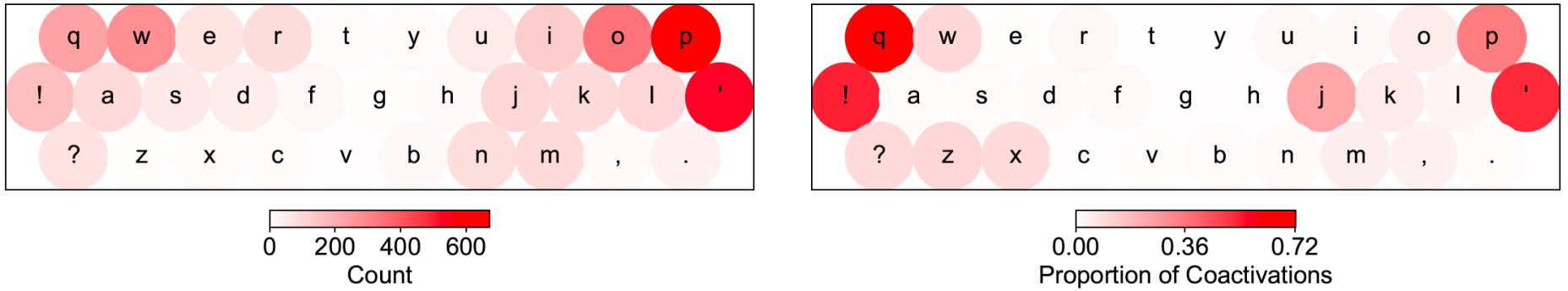


Typing in thin air—without a visible keyboard



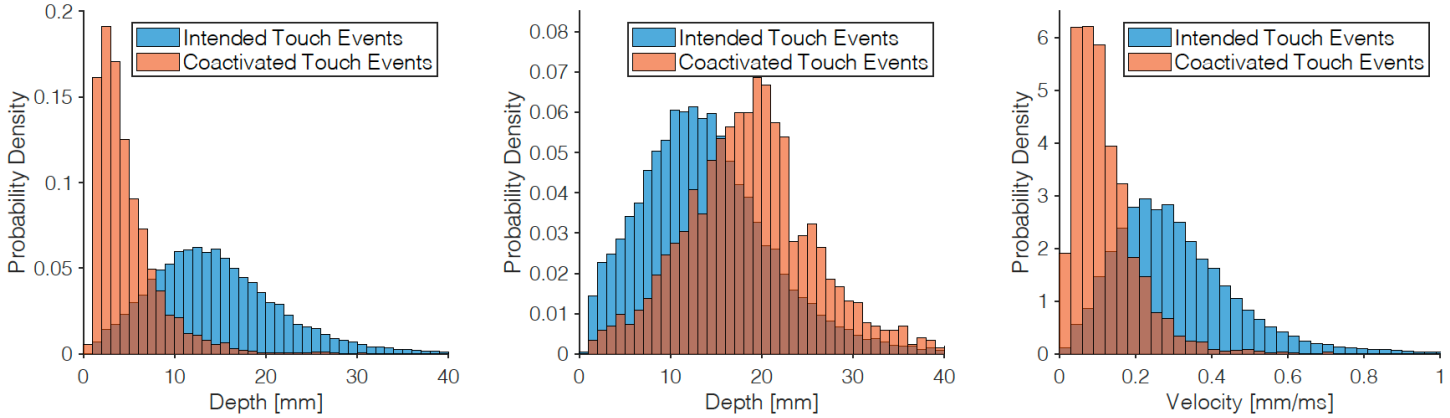
Dudley, J.J., Vertanen, K. and Kristensson, P.O. 2018. Fast and precise touch-based text entry for head-mounted augmented reality with variable occlusion. *ACM Transactions on Computer-Human Interaction* **25**(6): Article No. 30.

Managing coactivations



(a) Total coactivation counts.

(b) Proportion of touches that were coactivations.



(a) Current digit depth feature.

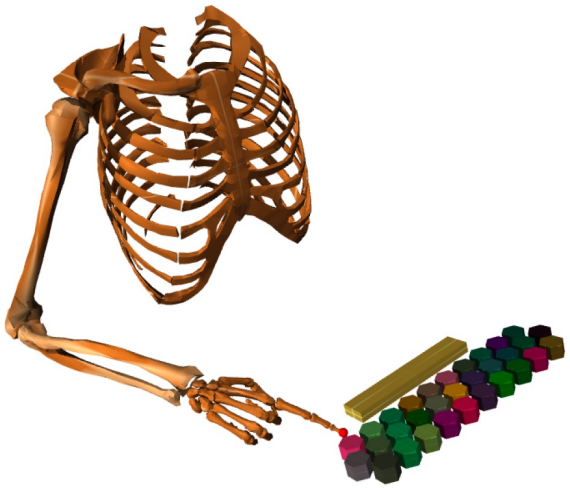
(b) Previous digit depth feature.

(c) Digit velocity feature.

Foy, C.R., Dudley, J.J., Gupta, A., Benko, H. and Kristensson, P.O. 2021. Understanding, detecting and mitigating the effects of coactivations in ten-finger mid-air typing in virtual reality. In *Proceedings of the 39th ACM Conference on Human Factors in Computing Systems (CHI 2021)*. ACM Press: Article No. 287.

Using reinforcement learning to train an agent to type in thin air

- Model not trained on actual data or tuned for any evaluation metrics
- Can predict actual mid-air and surface-aligned typing data from a user study
- Can be used to select suitable hyperparameters for a statistical keyboard decoder



Hetzel, L., Dudley, J.J, Feit, A.M. and Kristensson, P.O. 2021. Complex interaction as emergent behaviour: simulating mid-air text entry using reinforcement learning. *IEEE Transactions on Visualization and Computer Graphics* **27**(11): 4140-4149. Special issue on the 19th IEEE International Symposium on Mixed and Augmented Reality (ISMAR 2021).