The Representational Effect in Complex Systems: A Distributed Representation Approach

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Abstract

The representational effect refers to the phenomenon that different isomorphic representations of a common structure can generate dramatically different representational efficiencies, task difficulties, and behavioral outcomes. This paper presents a study of applying distributed representations to systematically analyze the representational effect in complex real world systems. Distributed representation is a representational system that is composed of internal and external information that is processed in a dynamic, interactive, and interwoven manner. The representational effect is observed and studied in a series of experiments involving various navigational instruments used in aviation. The cognitive task was decomposed into its components and the information distribution across internal and external representations for each component was identified. The experimental results showed that the task difficulties of different instruments correlate positively with the amount of external information for the component tasks, as predicted by the distributed representation analysis.

Introduction

The information necessary for the performance of almost any everyday task is distributed across information perceived from the external world and information retrieved from the internal mind. These tasks are known as distributed cognitive tasks (Zhang & Norman, 1994). The external representations constructed from the information extracted from external objects (such as written symbols) and the internal representations in the mind (such as schemas) dynamically integrate and interweave to result in a rich pattern of cognitive behavior. The principle of distributed representations is that a distributed cognitive task involves a system of distributed representations that consists of internal and external representations (Zhang & Norman, 1994, 1995). The task is neither exclusively dependent on internally nor exclusively dependent on externally processed information, but rather on the interaction of the two information spaces formed by the internal and external representations.

In the aviation industry, there are a wide variety of navigational systems. Among them there is a set of very basic navigational instruments. These instruments are selectively tuned to transmitting radio stations on the ground. The received signals are then presented in a display in the cockpit for the pilot to interpret. There is only so much information that a navigation instrument needs to display: azimuth or directional information, and distance information. However, different instruments present these two pieces of information differently and result in different degrees of precision and efficiency as interpreted by the pilot.

Cockpit information displays are examples of distributed representation systems. Navigational information in a cockpit information system can and is represented through a variety of isomorphic navigation instruments. Although these instruments are isomorphic and provide the same information, they vary in their relative degrees of directness and efficiency in their representation of scale information (Narens, 1981; Stevens, 1946; Zhang, 1995). The scale information of the orientation and distance dimensions in a cockpit information display is represented across internal and external representations and can dramatically affect the representational efficiency of the display and the navigator's behavior (Zhang, 1997). This research examines the cognitive properties of the representations that such instruments produce. The specific assumption to be tested is that with the most direct system, scale information is maximally represented externally, resulting in higher efficiency, faster and more direct responses.

Distributed representations

External representations are the representations formed from information gathered from the external environment. External representations include physical objects and/or symbols, relations and constraints between physical objects and their configurations relative to each other, and external physical rules, such as laws of physics. Through the human perceptual processes, the information necessary to form external representations is picked up by the sensory and perceptual systems. External representations are characterized as providing information that is directly perceived and applied toward a cognitive task without being explicitly interpreted. External representations contribute information that is otherwise unavailable from representations internally generated from memory, or from representations that are internalized from perceptual information (Zhang, 1997). Perceived information from within the external environment that must be represented internally in order for cognition to operate on it is, by definition, recreated as internal representations.

Internal representations are the representations that originate from within the mind and are not initiated from the perception of external stimuli. These internal representations are in the form of, but not limited to, mental images, propositions, production rules, and schemata. Cognitive processes retrieve information from long-term memory. This information may be selectively or incidentally retrieved, and is then employed to formulate internal representations.

Internal and external representational spaces together form a distributed representational space, which is where the representation of the task (its abstract structures and properties) resides. External representations are not re-represented redundantly as internal representations. In combination with internal representations, external representations can directly activate and provide perceptual information necessary for responses and actions.

Representational effect

The representational effect is the phenomenon that different isomorphic representations of a common structure can generate dramatically different representational efficiencies, task difficulties, and behavioral outomes (Zhang & Norman, 1994). It is ubiquitous in problem solving, reasoning, and decision making across many task domains.

Navigational Displays

The cockpit informational displays in this experimental study are navigational instruments that that provide directional guidance. As the experimental task is a position-fixing task, only the instruments that have the necessary information were provided and will be discussed here briefly. (A more in-depth review of cockpit navigational displays is provided in Zhang, 1997.). VOR (very high frequency omni-directional range), ADF (automatic direction finder), RMI (radio magnetic indicator), and the Moving Map display are four of the more prevalent navigation systems used for such a position fixing task. The generic moving map display refers to the more advanced cathode ray tube displays found in newer airlines that provide multiple information sources over a moving map within one display.

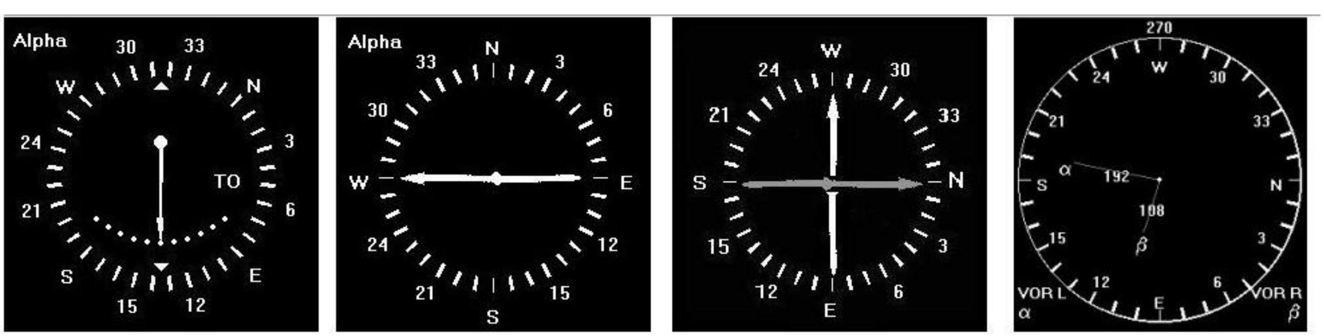
VOR indicator

The VOR equipment in the aircraft receives and interprets transmitted radio signals from the ground and shows directional information of the aircraft in relation to the VOR station on the ground. The VOR indicator is usually used to show the intended course of the aircraft and the lateral position of the aircraft in relation to that intended course. The VOR indicator in Figure 1A shows a selected 315º course. The TO indication at the right of center of the display indicates that proceeding on such a course will lead the aircraft to the station. The vertical needle (CDI, course deviation indicator), when in the center as shown, indicates the aircraft is on that selected course. If the CDI pivots to the left, this will indicate to the navigator that the aircraft is off the 315º course and needs to make a correction by navigating the aircraft towards the left to get back on course. The VOR indication (course selected) is independent of the heading of the aircraft.

The VOR indicator can also be used to determine the location of the aircraft relative to the VOR station. By tuning the VOR until the CDI centers with a TO indication, the displayed course will be the magnetic bearing of the aircraft to the VOR station. Likewise, by tuning the VOR until the CDI centers with a FROM indication, the displayed course will be the magnetic bearing of the aircraft from the VOR station.

ADF indicator

The ADF indicator in the aircraft can also be used for directional guidance to or from the radio station, or position fixing to determine one's location. The ADF indicator



(1A) VOR Indicator (1B) ADF Indicator (1C) RMI Indicator (1D) Moving Map Display

Figure 1: The four navigation instrument displays.

shows the orientation of an aircraft relative to the radio station (see Figure 1B). It only displays the relative bearing of the aircraft to the station, which is the angular distance between the lateral axis of the aircraft and the course to the station. In order to obtain a magnetic indication, which is necessary to navigate or determine one's position, the relative bearing indication must be summed with the magnetic heading of the aircraft (obtained off another instrument not shown). This sum is the magnetic bearing to the station; in order to derive the magnetic bearing from the station, the pilot would need to determine the reciprocal.

RMI indicator

The RMI indicator is similar in its display to that of the ADF indicator. The major difference between the ADF and RMI indicators is that the ADF display is fixed and the RMI display rotates as the aircraft changes direction. The RMI display is essentially the aircraft's heading indicator with the RMI pointer(s) providing navigational information (see Figure 1C). As a consequence, the RMI provides angular distance, and orientation of the aircraft relative to the radio station as magnetic indications. It is unnecessary for the navigator to do any computations to obtain magnetic bearing information.

Moving Map display

The primary navigational display mode of a Moving Map display shows a map of the immediate surrounding environment of the aircraft, as well as the radio stations. Magnetic bearing information is displayed alongside lines extending from the center to the radio stations. Angular distance is also provided.

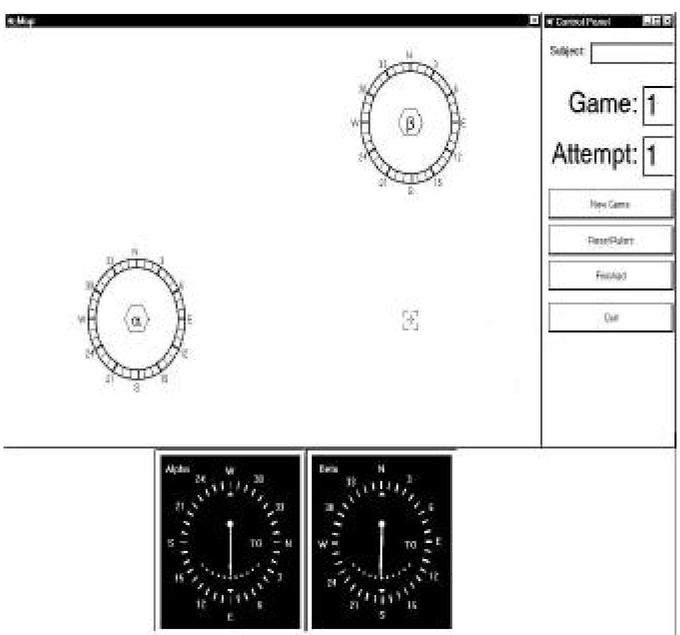


Figure 2: The experimental task display.

Experimental Study

The experimental hypothesis is that although the four navigation instruments provide the same and all the necessary information, the different distributions of the same information across internal and external representations make some instruments harder to use while make others easier to use, with the easiest one the instrument that has most external information. Experimental participants were provided with bearing information as displayed by the instruments, and were then required to determine the current position of the aircraft on a map.

Representational study of experimental task

A representational analysis of the experimental task identifies the abstract structures of the task and the representational properties that are responsible for the representational effect. To successfully perform the position-fixing task with the given bearing information, it is necessary to perform a triangulation using the radio stations as end points and extending from them along the bearings. The intersection of the bearings indicates the current position of the aircraft relative to the radio stations.

The four types of instruments have different representational spaces. The representational system with the largest amount of external information will be more efficient and direct (Norman, 1993; Hutchins, 1995; Zhang & Norman, 1994). Furthermore, the position-fixing task requires a triangulation method to determine the aircraft position. Both the VOR and RMI provide the necessary magnetic bearing information immediately. It is not necessary to represent the information internally. The ADF does not provide the information readily, and it is necessary to derive the magnetic bearing information through mental calculations using the heading information with the relative bearing information provided by the instrument. With the moving map display, the magnetic bearing information is also readily available. Furthermore, the information is presented in a graphical and spatial layout, with the instrument displaying the position of the aircraft relative to the radio stations. There is little effort required in comparing the displayed spatial relations with the map and determining the aircraft position. The other three instruments require cognitive effort in subtending bearing lines extending from the radio stations to create an intersection in order to determine aircraft position.

Table 1: Properties of the navigation systems.

Information readily available (externally represented)	Type of navigation system			
	VOR	ADF	RMI	Mov. Map
Aircraft heading			√	√
Magnetic bearing	√		√	√
Orientation		√	√	√
Angular distance between aircraft and radio station		√	√	√
Spatial and graphical layout of information				√

The prediction is that the moving map display will outperform the other three instruments because it provides the largest amount of external information and graphically and spatially presents the information in such a manner where the operation of determining the location of the aircraft is also provided externally. The representational effect will be that the experiment participants within that navigation instrument condition will outperform the other navigation instrument conditions. Table 1 summarizes the properties of the four navigation systems. For the other instruments, RMI should be easier than ADF, which should be in turn easier than VOR.

Method

Subjects. Eighty-five participants participated in the experiment for course credits in an introductory psychology course at The Ohio State University.

Materials and Equipment. Three Pentium computers were used with 17-inch monitors set at similar SVGA resolutions. The displayed image consisted of a large map covering most of the screen area, an instrument panel with the navigation instruments unique to each experimental condition, and a control panel that served as the experiment interface. The map area displayed two radio stations and a square icon that represented the aircraft. The positions of the radio stations and aircraft were randomized at every trial. Figure 2 shows a screen capture of an experimental trial.

Design and Procedure. The experiment was a between-subject design with four conditions, one navigational instrument for each condition. Each participant had 24 trials in the experiment. For each trial, the navigation instruments were displayed, providing the necessary and essential information. The participants would then read and interpret the navigation information and, by clicking and dragging the square aircraft icon, re-position it to where they believed the actual position of the aircraft was. They would commit their decision by clicking on the OK button. If the participants were correct to within a radius of 5% of the screen diagonal dimension, they moved on to a new trial. If they were incorrect, they were given two more attempts to locate the position.

Due to the complexity of the experimental task, the instructions were carefully administered, which limited the number of participants for each experimental session to two. Participants were first given a set of written instructions, then the experimenter provided with verbal explanations and further instructions. Each participant was

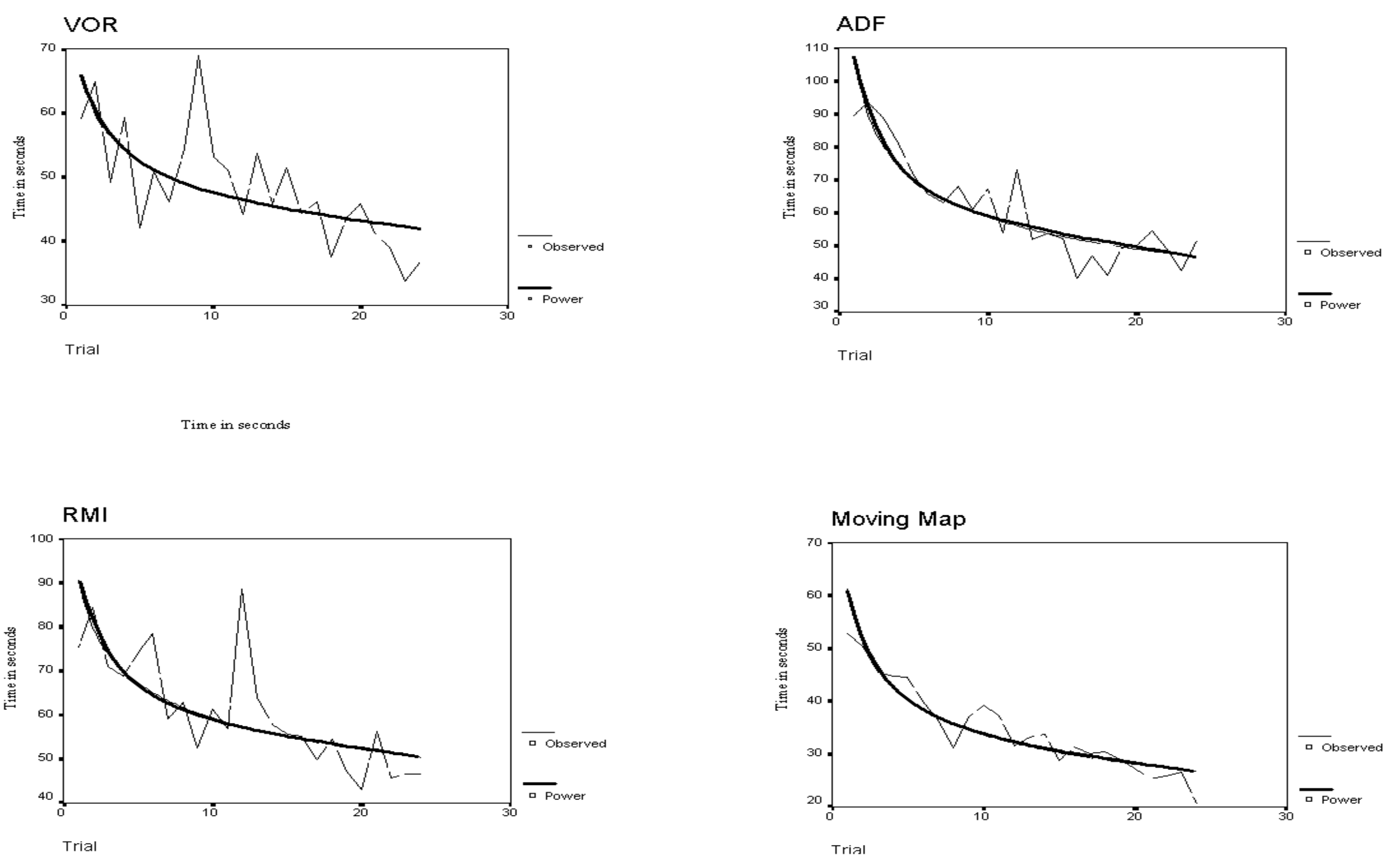


Figure 3: Performance data regressions.

given at least 3 trials to demonstrate his/her comprehension of the task prior to the start of the experiment. As the experiment required some manual dexterity to maneuver the computer pointer over the monitor screen, the computer mouse was configured for left-handed participants when necessary.

Results and Discussion

The performance data from all subjects were averaged by trial within each of the four conditions. Regressions were then performed for each condition.

There was an observation of a dramatic and robust power curve of learning for each condition that corresponded with the standard power law of practice. Figure 3 shows each condition with its raw averaged data and its best-fit regression. The variation in the VOR condition is the largest, as indicated by the lowest regression fit (r-squared value = 0.44). The other conditions have higher fits to raw data (r-squared values: ADF = 0.78, RMI = 0.57, Moving Map = 0.84).

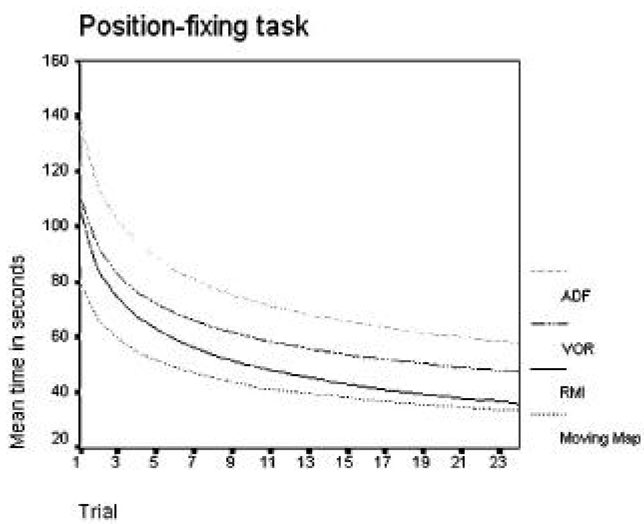


Figure 4: Regression comparison.

Figure 4 shows all four regressions within one graph for easy comparison. Table 2 below summarizes the task completion times for a trial set that was used for analyses.

Table 2: Comparison of mean times.

	VOR	ADF	RMI	Mov. Map	sig.
Trial 1	92.6	104.7	78.1	62.3	0.04
Trial 6	68.1	82.1	64.1	51.1	0.05
Trial 12	54.2	99.3	60.9	40.4	0.01
Trial 18	41.8	52.9	44.9	43.0	0.60
Trial 24	42.7	63.4	41.2	28.0	0.00

The prediction was for participants in the Moving Map condition to outperform all other conditions, to be followed with the RMI and ADF conditions, and the VOR condition participants were expected to be the slowest to complete the experimental task.

As the data show, there were significant differences between the four conditions at four of the five trials used for analyses in the ANOVA test. A post-hoc analysis performed using the Tukey test for multiple comparisons revealed that there were significant differences in task completion times (alpha level = 0.05) between the ADF and RMI conditions and between ADF and Moving Map conditions, with the ADF times higher than either of the other two conditions.

Performances levels of the four conditions got closer after 24 trials, although there was a significant difference between the ADF and Moving Map conditions. The individual power curves of learning between all four conditions resulted in this performance convergence. After 24 trials, the performance times between the conditions followed the predicted trend.

Discussion

According to the hypothesis, the representational effect observed will favor the performance of the Moving Map over that of the RMI, ADF, and VOR. This assumption arose from the representational analysis that decomposed the cognitive task and identified the components and properties that would be responsible for such a representational effect. It was identified that the Moving Map navigation display provides all the necessary information externally and in a spatial and graphical layout and other displays provide more information that needs to be represented and computed internally, with a high cognitive cost. All the necessary information for the task is available as directly perceptible forms of external representations for the Moving Map condition. Furthermore, the information is provided in an instrument display that maps directly to the map displayed on the monitor since the instrument itself is a map. None of the instrument components has to be represented or re-represented in an internal representation, thus reducing mental workload and increasing task efficiency.

The RMI condition posted consistently faster times against the ADF condition, with significance for trials 12 and 24. The RMI displays bearing information to the user in the magnetic compass scale, as opposed to the ADF instrument that provides the information in a relative degree scale. As a result, the navigator avoids costly mental workload by obtaining more of the information from the external representational space.

The VOR task completion times were not expected to be as fast as the Moving Map display. It was anticipated that VOR times would be slightly slower than ADF times. But there were no significant differences between the VOR and ADF. The difference, if it existed, might be too small to be observed. Additionally, there is an obvious and noticeable learning process that is occurring, as the participants become more proficient and familiar with the instruments and the task itself. This may be attributed to simple skill acquisition or familiarization of the interface.

Conclusion

The experimental results were generally consistent with the predictions of the distributed representation analysis. The prediction was that the instrument with more external information would be easier. This prediction was supported by the observed representational effect. The representational effect predicted that isomorphic representations could produce different behaviors due to the variant distributions of internal and external representational information.

The resulting behavior variance from the experiment indicates that some representations are more 'efficient' in extending the necessary information for a task. Although the different isomorphic representations result in different initial levels of performance and learning curves, performances appear to converge after a sufficient period of learning.

One argument can be made about the learning behavior: learning and practice may eliminate the representational effect after enough trials. However, further research needs to be done in more complex and dynamic settings. The current experimental task was a simple position-fixing task in a very controlled and static environment. In an unpredictable and complex environment such as that of the cockpit of an aircraft, the representational effect could be more pronounced and a possible regression to initial performance levels should be studied. Another issue that is worth of further study is whether the converged performance after learning for different representations will diverge again under extreme conditions such as high cognitive workload and time pressure.

Acknowledgements

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References

Hutchins, E., (1995). How a cockpit remembers its speed. *Cognition Science*, *19*, 265-288.

Narens, L., (1981). On the scales of measurement. *Journal of Mathematical Psychology*, *24*, 249-275.

Norman, D. A., (1993). *Things that makes us smart*. Reading, MA: Addison-Wesley

Stevens, S. S., (1946). On the theory of scales of measurement. *Science*, *103*, 677-680.

Zhang, J., & Norman, D. A. (1994). Representations in Distributed Cognitive Tasks. *Cognition Science*, *18*, 87-122.

Zhang, J., & Norman, D. A. (1995). A representational analysis of numeration systems. *Cognition*, *57*, 271-295.

Zhang, J., (1997). Distributed representation as a principle for the analysis of cockpit information displays. *International Journal of Aviation Psychology*, *7(2)*, 105-121.

Precursors to Number: Making the Most of Continuous Amount

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Abstract

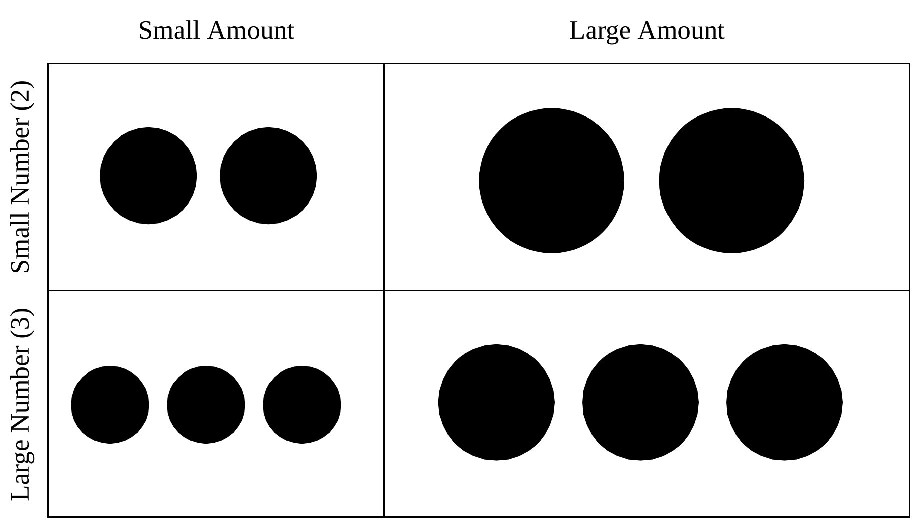
How does our understanding of number develop? There is evidence suggesting that even infants have primitive concepts of "more", "less", and "the same". Some researchers have concluded that humans have an innate number sense, present from birth. In this paper, we present a two-part model which explains these results in terms of continuous amount. The first part is a quantitative model addressing the results of infant habituation studies. The second, more tentative part of the model addresses object individuation, subitizing, and number estimation.

Amount vs Number

In this paper, we use the word *amount* to refer to the total area of the objects in view; this is a continuous quantity. *Number*, a discrete quantity, refers to how many objects are present. As shown in Table 1, these two aspects can be varied independently.

A complete model would have to take into account other features, such as total contour length (edge length), shape, and color. Except where otherwise stated, we disregard these details.

Table 1: Amount vs Number. Both pictures in each column have the same total area.



Habituation Studies on Infant Numerical Abilities

Three studies are addressed directly by the first part of our model: Starkey & Cooper (1980), Antell & Keating (1983), and Clearfield & Mix (1999). All three studies use the same habituation paradigm, described below.

An infant is shown a series of images of black circles or squares on a white background, such as those in Table 1.

The infant is shown several more images. They may differ in arrangement, but they are the same on some critical dimension, such as the number of dots. If the infant habituates (stops looking at new images as long), this is taken as evidence that the infant detected the invariant property and became bored with it.

After habituation, the infant is shown a test image which differs on the critical dimension. If the infant dishabituates