Eurographics Conference on Visualization (EuroVis) 2015
H. Carr, K.-L. Ma, and G. Santucci
(Guest Editors)

Volume 34 (2015), Number 3

Visual Analysis of Proximal Temporal Relationships of Social and Communicative Behaviors

Y. Han[1], A. Rozga[1], N. Dimitrova[2], G. D. Abowd[1] & J. Stasko[1]

[1]School of Interactive Computing, Georgia Institute of Technology, Atlanta, USA
[2]Department of Psychology, Georgia State University, Atlanta, USA

Abstract

Developmental psychology researchers examine the temporal relationships of social and communicative behaviors, such as how a child responds to a name call, to understand early typical and atypical development and to discover early signs of autism and developmental delay. These related behaviors occur together or within close temporal proximity, forming unique patterns and relationships of interest. However, the task of finding these early signs, which are in the form of atypical behavioral patterns, becomes more challenging when behaviors of multiple children at different ages need to be compared with each other in search of generalizable patterns. The ability to visually explore the temporal relationships of behaviors, including flexible redefinition of closeness, over multiple social interaction sessions with children of different ages, can make such knowledge extraction easier. We have designed a visualization tool called TipoVis that helps psychology researchers visually explore the temporal patterns of social and communicative behaviors. We present two case studies to show how TipoVis helped two researchers derive new understandings of their data.

Categories and Subject Descriptors (according to ACM CCS): Information Interfaces and Presentation (e.g. HCI) [H.5.m.]: Miscellaneous—

1. Introduction

Developmental psychology researchers examine children's social and communicative behaviors to understand early typical and atypical development. The study of these behaviors has important clinical implications as it can contribute to the early detection of autism and developmental delay [RFBG01, WAC*02]. It is crucial to detect these issues as early as possible so that support and intervention can be obtained earlier to help reduce their impact on the child's life [FP94]. These early signs are atypical behavioral patterns, for example, a 12-month old child not responding to his or her own name [NOY*07]. To find these patterns, psychology researchers code videos of certain predefined behaviors of interest and then quantify several key metrics, such as frequency, duration, and synchrony, to analyze the behaviors with statistical methods [Fel07]. However, with so many different temporal relationships in play among numerous social and communicative behaviors, it can be difficult to broadly gain knowledge about the presence and types of meaningful behavioral patterns across multiple children at different ages within a dataset.

Visual analysis is particularly suitable to help psychology researchers examine the temporal relationships of social and communicative behaviors because these relationships, especially when the behaviors overlap or nearly overlap, form unique patterns that are easy to detect when visualized. Throughout this article, we will use the term "proximal events" to refer to these behavioral events about which researchers care. Proximal events may or may nearly overlap in time and the time window used to define their closeness varies with the domain and context of use. Researchers have used, for example, Gantt chart-like visualizations [dBJFD13, Gan19], to show such events and patterns, but we seek to provide new interactive visualizations that can further the exploration.

We have created TipoVis, a visualization tool for exploring the temporal relationships of social and communicative behaviors. This work provides the following contributions: (1) we present the objectives and design rationale in analyzing such behavioral data for developmental psychology researchers, (2) we present a visualization technique and tool for the visual analysis of behavioral patterns, and (3) we assess the technique and tool via two case studies in developmental psychology to identify the utility of TipoVis.

2. Related Work

Our work assumes that with large collections of temporal data, certain relationships are easier to discover and analyze through visualization. Supporting this position, Aigner et al. summarized decades of research on visualizing temporal data in a recent book [AMST11].

Many visualizations have been created to explore temporal relationships of categorical temporal events. Some techniques such as Lifelines2 [WPS*09], LifeFlow [WGGP*11], and Outflow [WG12] address only point-based events without durations. Our focus is on interval-based events that have durations with start and end times, as these are the types of behavioral events typically coded from video in psychology research on children's social and communicative behaviors.

Allen and Ferguson present 13 different relationships of two time intervals, nine of which overlap in time, when studying Interval Temporal Logic [AF94]. When behavioral events overlap, they exhibit different patterns that are important in studying social and communicative behaviors. As a result, it is crucial to support the examination of the overlapping patterns in this domain.

A variety of visualization techniques have been developed to present the overlapping patterns of proximal events over time.

- Listing or adjoining events in parallel vertically, as seen in Gantt charts [Gan19], LifeLines [PMR*96], PlanningLines [AMTB05], history flow [VWD04], and [BDP08] (Figure 1a)
- Partially overlaying horizontal bars that represent events, as is seen in many calendar programs (Figure 1b)
- Fully overlaying semi-transparent horizontal bars that represent events, as seen in EventFlow [MLL*13] (Figure 1c)
- Partially overlaying vertical bars that map to events, as seen in Conversation Clock [BK07] (Figure 1d)
- Fully overlaying semi-transparent circles, as seen in Plexlines [LLK13]

These approaches have several limitations, however. For the techniques that overlay the bars less (e.g., Figure 1a, 1b), the overlapping patterns can be perceptually more difficult to observe than the ones that overlay more (e.g., Figure 1c, 1d) because of the proximity rule of Gestalt principles of organization [Tov08]. However, the three techniques that overlayed the bars more have other limitations. For EventFlow that uses semi-transparency (Figure 1c), the event in front will mask out the one in back, thus making it more difficult to perceive the overlap. The tool as a result added colored vertical bars on the ends of the horizontal bars to reduce the

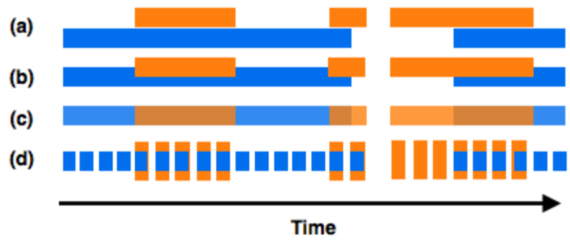

Figure 1: *Techniques for visualizing overlapping proximal events. (a) Listing or adjoining events in parallel vertically (b) Partially overlaying horizontal bars (c) Fully overlaying semi-transparent horizontal bars (d) Partially overlaying vertical bars*

impact of the problem. On the other hand, the technique used in Conversation Clock (Figure 1d) does not have the issues above but because of the use of separated vertical bars, the temporal resolution of the technique is lower than the others as shown in the imprecise mapping of the overlapping pattern. The semi-transparent circles in Plexlines reduce the issue of overlay by mapping the circle size to the duration of events [LLK13]. However, long events in this design can take up much more vertical space.

We build on these prior techniques to support the exploration of behavioral patterns. Additionally, we need to consider the comparison of multiple event sequences as psychology researchers need to generalize behavioral patterns across subjects.

3. User Tasks and Design Objectives

To understand the needs of potential users, we informally spoke with developmental psychology researchers to learn about their goals and process in examining social and communicative behaviors. We also showed them a variety of designs to elicit feedback about each. We learned that researchers typically need to accomplish the following tasks in exploring behavioral data.

- **T1: Explore the proximal temporal relationships of behaviors**
  Researchers are interested in this task for two common reasons. First, to find out whether and how a child responds to some behavior of their social partner. They need to understand the temporal relationships between the behaviors of both the child and the social partner. Depending on the context and social partner's behavior, the expectation for the nature and the timing of what is considered an appropriate or typical response by the child may vary. For example, "holding out an object" from a social partner has an expectation for a "take the object" response by the child shortly after the object was held out. Inspecting whether these behaviors occurred in the expected patterns for a given child can give insight into this child's developmental progress. Second, to find out if

a child uses multiple modes of communication, such as gesture and speech, to communicate with others, and if so, how the behaviors are used in concert. Researchers need to understand the temporal relationships between the multimodal communicative behaviors. For example, do young children start gesturing before speech to refer to an object? Understanding what is a typical temporal pattern of multimodal communicative behaviors is important for identifying atypical patterns that may indicate potential developmental delays.

Design Objective: Identify and highlight proximal temporal patterns of behaviors.

- **T2: Find subgroups of children that exhibit similar behavioral patterns**
  Researchers look for typical and atypical behavioral patterns among subgroups of children for generalization. The first step in finding such patterns is to identify a group of subjects that exhibit similar behaviors. How "similarity" is defined and measured varies based on the analytic goals of the researchers and patterns emerging from the data.

  Design Objective: Easily compare behavioral patterns between children.

- **T3: Map behavioral patterns with subgroups of children predetermined by certain grouping criteria**
  Children can be divided into subgroups by certain grouping criteria such as age, gender, parent-reported assessment, etc. Researchers are interested in exploring how these *apriori* grouping criteria map to the children's behavioral patterns within each subgroup and compare among different subgroups. For example, how do children at a certain age typically behave? Or how do children that passed a developmental assessment behave differently from those that failed?

  Design Objective: Map predetermined grouping criteria to children and subgroups of children.

4. Visualization Design

From the user tasks and design objectives outlined above, we designed a visualization technique to portray the temporal relationships of proximal events. The data we are visualizing include video-based coding of onsets and offsets of specific behaviors. The behaviors are often grouped into broader classes such as gaze or gesture. It is fairly common in developmental psychology research to code video data this way for analysis. To implement the technique, we created TipoVis, a system that supports visual exploration of proximal temporal patterns of two variables at a time. We only considered two variables as this already affords the examination of a wide range of temporal relationships [AF94] and is sufficient to answer a wide variety of research questions in developmental psychology. TipoVis is implemented with D3 [BOH11] in a web browser. Each visualization design aspect below is mapped to one or more user tasks and by connection, design objectives.

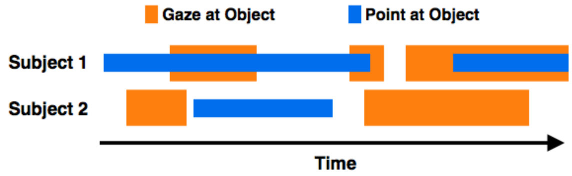

Figure 2: *TipoVis Visualization Technique. Events from the two behaviors (variables) have different colors and bar heights.*

4.1. Base Representation

The basic visual representation of proximal events of behaviors is an overlapping pattern of interval-based events as represented by colored bars (see Figure 2 and accompanying video). Each bar is an event from a variable, which is a specific behavior in our work. For example, in Figure 2, an orange bar is a "Gaze at Object" event whereas a blue bar is a "Point at Object" event. The start and end of an event are mapped to their relative temporal positions on the x-axis. Events from the two behaviors also differ in the height of the bars and are vertically centered so that they can both be clearly visible when they overlap. We designed the bars of the orange variable to be visually more salient in the background because we want them to also be used as a *reference* against which other variables can be aligned and overlapped. The visual patterns they form are critical for examining typicality of the behaviors so it is important to use a visual representation that works well no matter what the temporal relationships between the events are.

4.2. Emphasize Overlapping Pattern

Social and communicative behaviors often overlap or nearly overlap in time, creating temporal patterns that psychology researchers look for. Therefore, it is important to emphasize these moments. In the example in Figure 2, Subject 1 used the pointing gesture while gazing at the object multiple times but Subject 2 did not. Here, with only two subjects, it is easy to detect such overlaps. However, as the number of subjects increases and their visual representations become smaller and more densely packed, identifying the overlapping events becomes more difficult. As a result, TipoVis includes several methods for more easily finding these patterns.

1. Highlight Overlapping Pattern (T1)
   TipoVis can highlight the overlapping patterns from different variables with a red color as shown in Figure 3b. The parts of the bars that did not overlap are faded to

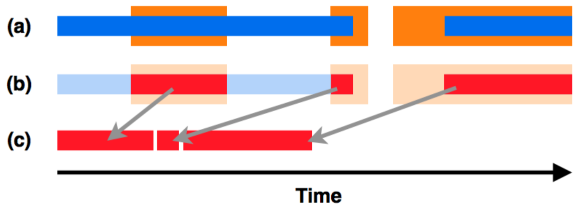

Figure 3: *Highlight and left-align overlapping pattern. (a) Normal view (b) Highlight overlapping pattern: colors of the bars fade, and the overlapping pattern highlighted in red. (c) Left-align overlapping pattern: the highlighted red overlapping bars moved to the left.*

make the highlighted parts stand out. This view can effectively reduce the visual saliency of the original bars and give the user a clear view of when and how the events overlap.

2. Extending Overlapping Time Window (T1)
Frequently, the events of interest do not overlap but are within close temporal proximity. For example, if we are exploring whether someone responded to a name call, we are observing whether the responsive behavior occurred within a small time window during and after the name call was made. In Figure 4, if the orange bars represent the name calls and the blue bars represent the responses, the originally highlighted overlapping pattern in Figure 4a will not be able to include the response to the second call in the end. To highlight these events, TipoVis allows the user to interactively extend the time window from the orange variable, creating additional overlapping patterns that can be highlighted as shown in Figure 4b. The extended parts of the time windows are shown as green bars. This extension can be configured by a special interactive control as shown in Figure 6c (best seen interactively in the accompanying video). This control mimics the actual visual representation of the events so that it also works as an interactive legend where the user can make changes with it and see how those changes in the configuration (e.g., highlight/left-align overlapping pattern/extend time window) influence the visual representation. There are two sliders on the control that can extend the overlapping time window for up to 5 seconds on each side of the orange variable. This time window is typically enough for finding the behavioral patterns of interest.
3. Left-Align Overlapping Pattern (T2)
If the user would like to remove the visual influence of the non-overlapping parts of the bars and compare the duration and frequency of the overlapping patterns, TipoVis can completely remove the original bars and slide the overlapping patterns to the left side as shown in Figure 3c. The new view becomes a bar chart of its own that makes it easier to compare overlapping patterns between different subjects.

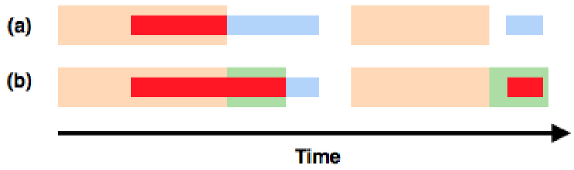

Figure 4: *Extending the overlapping time window by the orange variable to find overlapping patterns. (a) Normal view with highlighted overlapping patterns (b) Redefine overlapping time window by extending events of the orange variable in the end to find new overlapping patterns. The green bars are the extended part of the overlapping time window. We can see that a new overlapping pattern emerged and the existing overlapping pattern, shown as the red bar in (a), is extended in (b).*

4.3. Comparison across Event Sequences

Psychology researchers need to know whether behavioral patterns are generalizable across subjects. To facilitate this task, TipoVis supports a variety of functions to help compare behavioral patterns between subjects. Each row in Figure 5 shows a session from a subject. We refer to each row as an *event sequence*. Event sequences can be broken down by meaningful and more comparable time periods, such as when the child is playing with a specific object. These time periods show up as columns in the tool. A gray background behind the colored bars (as seen in later figures from the case studies) shows the durations of these time periods.

The visual design of the overlaying bars facilitates comparison between event sequences. When the data from the event sequences are presented directly above each other in stacked rows, events from the first variable, shown as orange bars, can be visually connected with events of neighboring event sequences. This design makes it easier to compare temporal patterns between event sequences as shown in Figure 5c. In TipoVis, we intentionally choose to only overlap two variables at a time because adding more variables will visually distance the variable in the middle from the same variable in the neighboring event sequence, making it harder to compare patterns. Additionally, overlapping only two variables at a time allows us to minimize the height of the bars, thus enabling us to show more event sequences in the limited vertical screen space.

Several features of TipoVis help facilitate the comparison of event sequences:

1. Group and Filter Event Sequences (T2,T3)
TipoVis can vertically group and filter event sequences with similar properties based on their metadata. For example, event sequences with children of the same age and can be grouped together as shown in Figure 5b. Additionally, users can also choose to filter out other event sequences by opting to only keep data from children of a specific age. When fewer event sequences are visi-

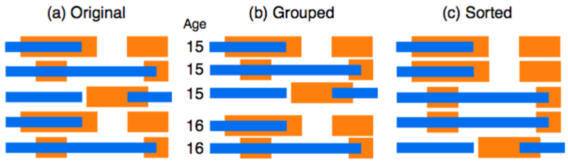

Figure 5: *Compare event sequences. (a) Original view (b) Event sequences grouped by age (c) Event sequences sorted by some criterion*

ble, TipoVis will increase their vertical size to better utilize the screen space. Depending on the metadata collected, the event sequences can also be grouped by various scores collected through developmental screening instruments such as the M-CHAT [RFBG01].

2. Sort Event Sequences (T2)
   TipoVis can also vertically sort event sequences by the broken down time periods (columns) to help visually group, align, and compare proximal temporal patterns as shown in Figure 5c. The sorting algorithm can depend on metadata (e.g., age) or the event data (e.g., frequency or duration of a certain variable). The scope of sorting of event sequences depends on the groupings. When the event sequences are grouped, the sorting applies to each group separately (sort within group). On the other hand, if they are not grouped, the sorting applies globally to all event sequences.

These functions in TipoVis help psychology researchers explore behavioral patterns with the ability to flexibly redefine the overlapping time windows. Highlighting and left-aligning of the overlapping patterns facilitates large-scale exploration. Grouping, filtering, and sorting event sequences helps simplify the comparison of overlapping patterns.

Following a design study methodology [SMM12], we applied TipoVis to two behavioral datasets to examine how it can help researchers gain insights into their data. In the following sections, we explain how TipoVis helped developmental psychology researchers with their data exploration tasks.

5. Case Studies

We conducted two case studies to understand the effectiveness of our visualization technique and system in supporting the understanding of social and communicative behaviors. We worked with two developmental psychology researchers who routinely explore this type of data. They used TipoVis to find behavioral patterns with *apriori* research questions and hypotheses.

5.1. Study 1 - Unstructured Toy Play

The 3rd co-author (Dimitrova) is a developmental psychology researcher whose research investigated how children develop object-use knowledge while interacting with their caregivers [DM13]. She used TipoVis on a "toy play" behavior dataset for about two months to see if she could find new insights into the data.

To understand how young children start using objects in conventional ways, the researcher observed how children interacted with their mothers and a set of toys: (1) a sorter game, (2) a baby doll with a dinner set, (3) a doctor's kit, and (4) a stacking tower. She videotaped the toy play sessions of 6 children with their mothers every two months between ages 8 to 16 months. Each recording session took about 30 minutes, 7 minutes for each toy. As there were data from 6 children, each with 5 sessions recorded, there were 30 sessions in total.

Two research questions she wished to answer with this dataset are: (1) How do caregiver and child act on the toys? (2) How do caregiver and child communicate with each other?

The recorded data were manually annotated to help answer the research questions. To address question 1, the children's uses of the toys were coded into 5 levels: from non-conventional use (NCU, e.g., mouthing toys) to conventional use (CU, e.g., inserting the correct shape into the sorter toy). The mother's demonstrations (CU) of using the toys were also coded to see how they relate to the child's object use. To address question 2, both the child's and the mother's communicative behaviors, such as eye contact and gestures, were coded. Each annotation was coded by the onset and offset of the behavior. In total, there were 26 types of behaviors coded.

Each toy play session could be broken down into four toy play periods according to the toy involved. We will use visualization of two of the four toy play periods to demonstrate how the researcher used TipoVis. Based on the research questions, we imported the data with the mappings as shown in Figure 6[†]. The main x-axis is divided into the two toy play periods, Sorter and Baby Doll. In each toy play period, the x-axis is time. Each event sequence along the y-axis is a specific toy play session at a given age (A1 = first out of 5 sessions for each child) from a specific mother-child pair (S1 = subject 1). The sessions can be grouped by age or subject. These two grouping types can be interactively selected with the drop-down menu on the top-left corner of TipoVis as shown in Figure 6. The gray bar in the background shows how long a specific toy play period lasted in each session.

5.1.1. Usage Scenarios

1: How did mothers' demonstration of toy use relate to children's non-conventional use of the toy across age?

[†] Many of the figures in this article are large and occupy a full computer screen. The limited room here in the paper requires they be shrunk to a level where seeing the overview is possible, but observing details is difficult. We refer the reader to the accompanying video that makes the visualization and interactions much clearer.

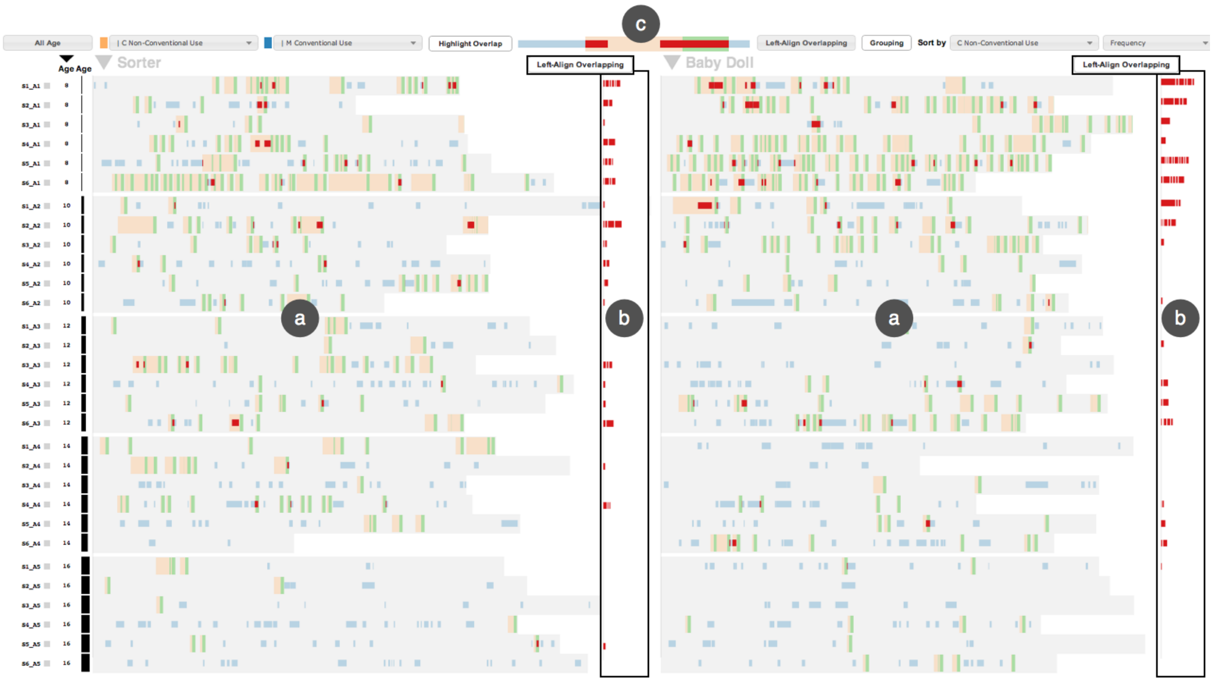

Figure 6: *Finding the relationship between Child Non-conventional Use (of toy) and the Mother Conventional Use (of toy) in extended overlapping time windows. (a) Highlighted overlapping pattern (b) Left-aligned overlapping pattern (c) Extended overlapping time window to find Mother Conventional Use (of toy) after Child Non-conventional Use (of toy)*

This question was driven by a hypothesis that mothers typically provide models for their children's conventional use of toys and correct their children when they perform non-conventional uses with the toys. For example, if a child mouths a ring from the stacking tower toy, the mother typically takes the ring and places it on the stacking toy. In this case, the researcher looks for temporal relationships of children's and maternal use of toys.

To observe how the behaviors change with age across subjects, the researcher selected the grouping of sessions by age on the y-axis as shown in Figure 6. She used the child's NCU behavior as the first variable (orange bar) and the mother's demonstration (CU) behavior as the second variable (blue bar). Because the onset of the mother's demonstration should start during or following the child's NCU of the toy, she extended the overlapping time window to include the child's NCU (orange bar) and a few seconds after (green bar) the child's NCU. Then she looked for overlapping patterns of the mother's demonstration (red bar) that occurred within this time window as shown in Figure 6a. TipoVis allowed her to see that there were more overlapping pattern occurrences when the children were younger (more red near the top). She adjusted the overlapping time window with the sliders to find the best threshold that showed the change in behaviors. However, as both behaviors occurred quite frequently, the parts of the behaviors that were not highlighted somewhat obscured the highlighted parts that were of interest. Therefore, by clicking on the Left-Align Overlapping button, she temporarily removed parts of these proximal events that were not overlapping and aligned the overlapping parts to the left side as shown in Figure 6b. With this view, she could see the decreasing trend of frequency and duration of these overlapping patterns, showing that, with age, children progressively produced fewer non-conventional toy uses, resulting in mothers producing fewer correcting behaviors. Nevertheless, mothers continued to produce demonstrations of object use across children's ages, as can be seen from the blue bars throughout in Figure 6a, just not immediately following their children's NCU. These later demonstrations were likely serving not as "corrections" of children's non-conventional uses but as ways to introduce children to a wider range of conventional use. TipoVis helped quickly reveal this pattern and generate a hypothesis to be further explored in this dataset.

2: Did children react faster to a toy being held out by their mothers as they grew older?

When a mother holds out an object, it is a communicative gesture asking the child to take the object. This interaction shows the developmental progression of children's ability to understand the maternal communicative intention (i.e., "take the object") in order to provide a relevant response.

Using the highlight function, the researcher explored these overlapping patterns. She set the sessions on the y-axis to be grouped by age in order to examine the change over

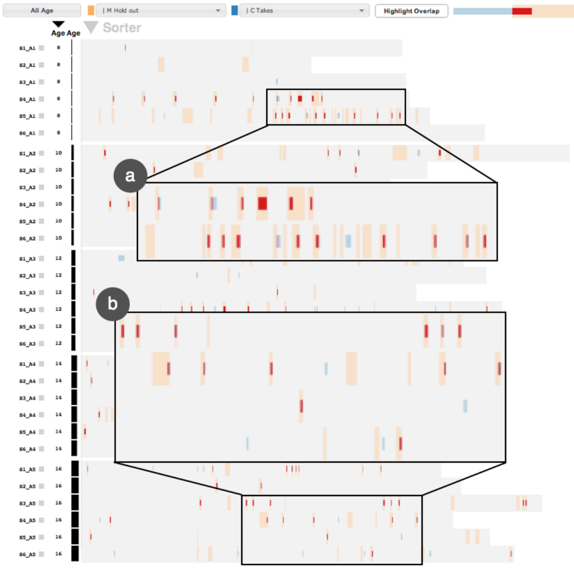

Figure 7: *Examining the overlap between child taking a toy and mother holding it out. Sessions are grouped and sorted by age. Older children (b) seem to take the toy sooner than younger children (a).*

time as shown in Figure 7. However, there was no clear overall change of frequency of these give-take events as these children aged. But taking a closer look at the overlapping patterns, younger children seemed to take longer to respond to the gesture: there seemed to be more orange before the overlapping pattern (red) when the children were younger as shown in Figure 7a. On the other hand, when children were older, the synchrony of the two behaviors was higher as shown by the frequent exact overlap of the orange and overlapping pattern (red) (Figure 7b). This observation suggested that as children aged, they understood the meaning of the holding-out gesture and thus took the object as soon as the gesture was produced. The pattern was subtle but visible.

5.2. Study 2: Structured Multimodal Dyadic Interaction

The 2nd co-author (Rozga) is a developmental psychology researcher who is interested in understanding whether the behavioral data collected using a new play-based developmental assessment can be used to identify children with developmental concerns [RAR*13]. She has been working as part of our research team for about 1.5 years since the conceptualization of the tool.

The dataset she collected contains 225 sessions from 178 children engaged in a 5-minute play protocol with an adult (examiner) over a table [RAR*13]. Children were aged 15-30 months at recruitment. There are five stages in the play protocol where the examiner (1) greets the child, (2) plays ball with the child, (3) reads a book with the child, (4) puts the book on her head pretending it's a hat, and (5) tickles the child. After the protocol, the examiner calls the child's name several times to see whether and how the child responds. Both data from the play protocol and the response to name probes are part of the dataset. Parents were asked to fill out two, widely used, standardized developmental screening questionnaires that can be used to identify children showing early signs of autism (M-CHAT) or social-communication delays (CSBS Infant Toddler Checklist) [RFBG01, WAC*02].

One way to evaluate a new developmental assessment protocol is to examine how well it matches the results from existing validated assessment tools. Therefore, the first research question was whether the behavioral patterns elicited in the play protocol reliably capture differences between children who were flagged as showing developmental concerns on the parent-reported assessment compared to children who passed the assessment. A second, more exploratory research question was whether behavioral patterns in the new play protocol reveal a subgroup of children who did not fail the parent-reported developmental assessments yet appear to behave atypically compared to other children in this sample.

To answer these questions, the researcher examined behavioral patterns in this dataset that contains 20 child communicative behaviors (e.g., child gaze at examiner face; child point) categorized into four modes of communication (gaze, speech, gesture, vocal affect), along with 22 examiner behaviors (e.g., reach toward children; "Where's the yellow duck?") intended to elicit child responses. The onsets and offsets of these behaviors were manually coded from video recordings of the play protocol by multiple human annotators. A subset of the 144 fully-annotated sessions were included in the analysis.

In TipoVis, the play protocol can be broken down into its five constituent stages and the two response to name probes on the main x-axis columns. However, in the usage scenarios below, the psychology researcher chose not to break down the event sequences into separate columns, as she wished to examine global behavioral patterns across the entire interaction. The gray bars in the background show the full length of the play protocol, followed by the two short response to name probes. The y-axis lists the interaction sessions. The outcomes (pass/fail) of the parent-reported assessment were included as metadata that could be used to group and filter the play sessions. They can be selected in the drop-down menu at the upper-left corner of the tool as shown in Figure 8.

5.2.1. Usage Scenarios

1. Do the subgroup of children who failed a parent-reported assessment (M-CHAT, CSBS) show different behavioral patterns than those that did not?

The researcher started off answering this question by identifying sessions with children who had failed either of the parent-reported developmental assessments, and highlighting these sessions. Then, she observed how these children behaved in the play session by inspecting several key behavioral patterns that she expected to be indicators of developmental delays, such as the reduced coordination of gaze with gesture and speech. If the behavioral patterns elicited in the social play protocol were able to differentiate children the same way that the parent-reported assessments do, these children should form a subgroup based on their behavioral patterns. Surprisingly, they did not.

For example, being able to shift gaze between an object and an interactive partner's face is an important developmental milestone [BA84]. The researcher selected "Child Gaze at Object (Book/Ball)" and "Child Gaze at Examiner Face" behaviors and extended the overlapping time window by a short period of about 0.5 seconds to identify occasions when the child gazed at the examiners face right after gazing at the ball or book. She then highlighted the overlapping pattern (red) as this is the gaze shift pattern she wanted to examine. Next, she removed the grouping of the sessions by parent-reported assessments and sorted them globally on the y-axis by the frequency of this gaze shift pattern. As shown in Figure 8, the children who failed the parent-reported assessments not only did not cluster toward the bottom of this ordered list, as she expected them to, but were almost evenly distributed in the dataset (highlighted yellow). The same observation held when she selected just the subgroup of children who failed only M-CHAT, and when she repeated this exploration with two other behavioral patterns (gaze to examiner's face co-occurring with a gesture, and gaze to examiner's face co-occurring with speech). These observations indicated that the new play protocol may not be capturing the same information about children's behavior as the parent-reported questionnaires. Inspecting the data further, she noted that the overall rates of the behavioral patterns she examined were quite low across the entire sample, suggesting that perhaps the new protocol was simply too short to elicit sufficient behaviors to be comparable to the parent-reported assessments.

2. Do behavioral patterns in the social play protocol reveal a subgroup of children who did not fail the parent-reported developmental assessments yet appear to behave atypically compared to others?

The researcher wanted to see if TipoVis can be used to identify a subgroup of children who behaved atypically in the play session despite the fact they passed both parent-reported developmental assessments. Finding such a subgroup of children would indicate that the new play protocol may identify subtle behavioral atypicalities not captured by parent report.

This time, she started by identifying and highlighting children who did not fail either parent-reported developmental assessments yet failed to show any overlap of gaze to the examiner's face with a gesture. She started exploring where these children would fall when she sorted the sessions by the frequency of the other key behavioral patterns, i.e. overlap of gaze to the examiner's face with speech, and gaze shifts from objects to the examiner's face. She found that this subgroup (highlighted yellow) seems to be more consistently clustered together based on their overlapping behavioral patterns, as shown in Figure 9. She noted that this new subgroup warrants further investigation, to determine whether these children represent another subgroup of children with developmental concerns, or whether other factors (e.g., shyness) may have contributed to their atypical behavior during the play protocol.

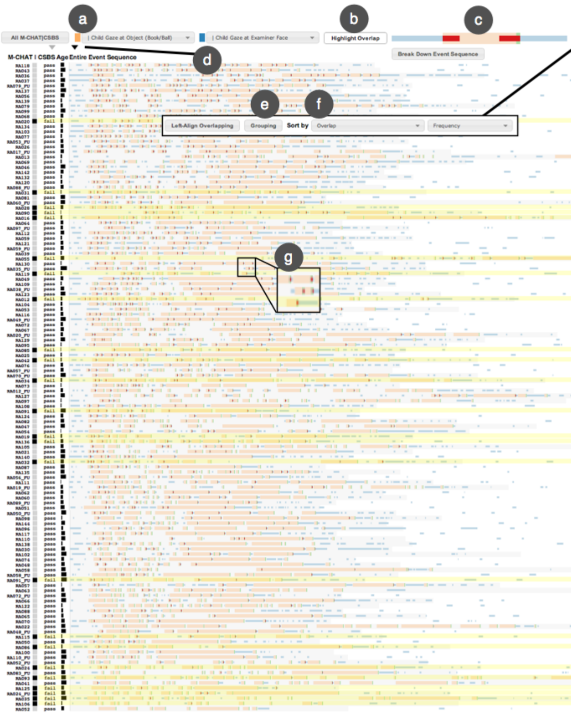

Figure 8: *Children who failed a parent-reported assessment (highlighted yellow) do not seem to form a similar amount of gaze shift patterns. Notice the gaze shift distribution of highlighted sessions along the y-axis that indicates this behavioral pattern did not separate this subgroup of children from the rest of the group. (a) Selected behaviors (b) Highlighted overlap (c) Extended overlapping time window by about 0.5 seconds to find gaze shift from object to examiner's face (d) Sessions sorted with data in entire event sequence (e) Sessions ungrouped (f) Sorted by overlap frequency (red) (g) Five gaze shift occasions (red)*

5.3. Discussion

Both developmental psychology researchers agreed that the exploration of behavioral patterns is a major strength of TipoVis. The tool can facilitate quick exploration of patterns of social and communicative behaviors of up to ap-

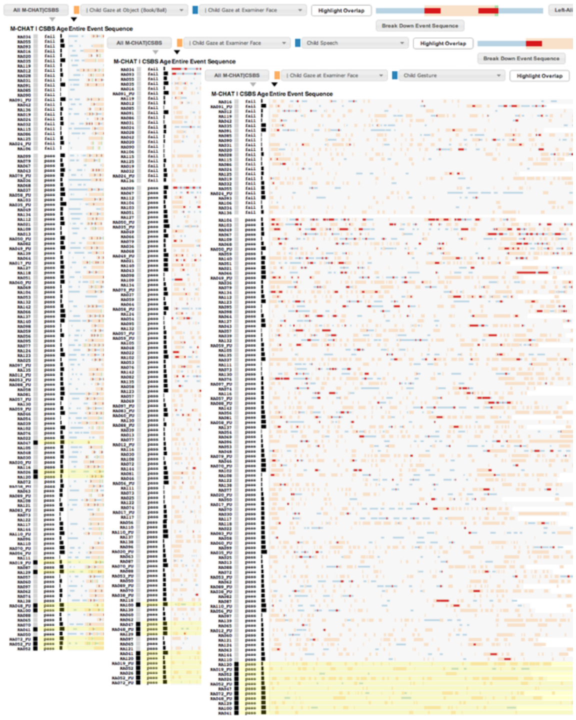

Figure 9: *Sessions with children who did not fail the parent-reported assessments but showed similar atypicalities over multiple behavioral patterns when compared to the rest of the group. See the yellow-highlighted sessions mostly clustering at the bottom of the session lists.*

proximately 100 sessions as shown in the second case study. The overlapping time window extension and overlaps directly capture the key behavioral patterns for examining developmental milestones. The ability to sort, group, filter, and highlight sessions allowed flexible exploration and analysis of subgroups. Additionally, having a dedicated column to visually show the age of the children at all times was helpful to the analysis process as correlating behaviors with age is a core aspect of their work.

On the other hand, the researchers still wished to see more numbers in the tool such as showing the number of seconds that were being extended in the overlapping time window or including descriptive statistics. We made an explicit decision initially not to include numbers to encourage exploration of patterns and to minimize clutter on the view. But in hindsight, this information could be presented to support further explorations of the data.

6. Conclusion

We designed and demonstrated how a visualization technique and tool, TipoVis, can help developmental psychology researchers derive new understandings in their own behavioral datasets. TipoVis supports the flexible exploration of behaviors that occur together or within close temporal proximity. The case studies in the previous section begin to illustrate how the system can be used in this domain.

TipoVis is not without limitations, however. First, it only supports finding overlapping patterns of two variables at a time. As discussed in Section 4, we intentionally made this design choice because it is easier to visually compare overlapping patterns among multiple event sequences when there is only one set of overlapping bars. This decision also allows us to minimize the height of each event sequence for better scalability. However, many research questions may require the investigation of overlapping patterns of more than two variables. As the number of variables increases, the number of these patterns will increase exponentially. Therefore, whether a timeline-based design will still be suitable for finding these overlapping patterns of more than two variables will need further investigation.

Second, TipoVis can show a reasonably large number of sessions using the vertical space as shown in Figure 8. Using the sorting, grouping, and filtering features, it is not difficult for the users to find and move patterns of interest into the visible area if the number of sessions were in the hundreds. However, if the number of sessions increases by an order of magnitude, additional features that aggregate or filter the data may need to be added to handle the scale of the dataset. Additionally, the horizontal space for showing the interval-based pattern is another point of concern for scaling. If the time period investigated is long, the user will need to scroll to see more data from other time windows.

Even though the tool and technique have limitations on scaling, we believe it can still be applied to a broad range of application domains for understanding the relationships between two variables. Exploring proximal temporal relationships between two variables at a time is not only of interest to developmental psychology researchers in finding typical or atypical behavioral patterns. Any domain that looks for relationships between interval-based temporal events within a limited time window can benefit from our visualization. For example, TipoVis can help medical researchers explore how a type of medication may have induced a specific side effect and how it generalizes among a large group of subjects. The length of the delay and the prevalence of this side effect can easily be explored with the system. In summary, TipoVis could be widely applied to help find events that may be correlated and explore how this relationship generalizes among multiple event sequences.

7. Acknowledgements

This work was supported by the NSF Expedition Award number 1029679. We would like to thank the Child Study Lab, notably the lab manager Audrey Southerland, at Georgia Tech and Christiane Moro for the datasets used in the case studies.

References

[AF94] ALLEN J. F., FERGUSON G.: Actions and events in interval temporal logic. *Journal of Logic and Computation 4*, 5 (Oct. 1994), 531–579. doi:10.1093/logcom/4.5.531. 2, 3

[AMST11] AIGNER W., MIKSCH S., SCHUMANN H., TOMINSKI C.: *Visualization of Time-Oriented Data*. Springer, May 2011. 2

[AMTB05] AIGNER W., MIKSCH S., THURNHER B., BIFFL S.: PlanningLines: novel glyphs for representing temporal uncertainties and their evaluation. In *Ninth International Conference on Information Visualisation, 2005. Proceedings* (July 2005), pp. 457–463. doi:10.1109/IV.2005.97. 2

[BA84] BAKEMAN R., ADAMSON L. B.: Coordinating attention to people and objects in mother-infant and peer-infant interaction. *Child Development 55*, 4 (Aug. 1984), 1278–1289. 8

[BDP08] BEARD K., DEESE H., PETTIGREW N. R.: A framework for visualization and exploration of events. *Information Visualization 7*, 2 (2008), 133–151. doi:10.1057/palgrave.ivs.9500165. 2

[BK07] BERGSTROM T., KARAHALIOS K.: Seeing more: Visualizing audio cues. In *Human-Computer Interactionâ INTERACT 2007*, Baranauskas C., Palanque P., Abascal J., Barbosa S. D. J., (Eds.), no. 4663 in Lecture Notes in Computer Science. Springer Berlin Heidelberg, Jan. 2007, pp. 29–42. 2

[BOH11] BOSTOCK M., OGIEVETSKY V., HEER J.: D3: Data-driven documents. *IEEE Transactions on Visualization and Computer Graphics 17*, 12 (Dec 2011), 2301–2309. doi:10.1109/TVCG.2011.185. 3

[dBJFD13] DE BARBARO K., JOHNSON C., FORSTER D., DEAK G.: Methodological considerations for investigating the microdynamics of social interaction development. *IEEE Transactions on Autonomous Mental Development 5*, 3 (Sept. 2013), 258–270. doi:10.1109/TAMD.2013.2276611. 1

[DM13] DIMITROVA N., MORO C.: Common ground on object use associates with caregivers' gesturese. *Infant behavior & development 36*, 4 (Dec. 2013), 618–626. PMID: 23891648. doi:10.1016/j.infbeh.2013.06.006. 5

[Fel07] FELDMAN R.: Parent-infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. *Journal of Child Psychology and Psychiatry, and Allied Disciplines 48*, 3-4 (Apr. 2007), 329–354. doi:10.1111/j.1469-7610.2006.01701.x. 1

[FP94] FIRST L. R., PALFREY J. S.: The infant or young child with developmental delay. *The New England Journal of Medicine 330*, 7 (Feb. 1994), 478–483. doi:10.1056/NEJM199402173300708. 1

[Gan19] GANTT H. L.: *Work, wages, and profits*. New York : The Engineering magazine co., 1919. 1, 2

[LLK13] LEE J., LIN S., KARAHALIOS K.: Visualizing patterns of social and communicative behavior in children using plexlines. In *Proceedings of the 2013 Workshop on Visual Analytics in Healthcare* (Nov. 2013), pp. 28–32. 2

[MLL*13] MONROE M., LAN R., LEE H., PLAISANT C., SHNEIDERMAN B.: Temporal event sequence simplification. *IEEE Transactions on Visualization and Computer Graphics 19*, 12 (Dec. 2013), 2227–2236. doi:10.1109/TVCG.2013.200. 2

[NOY*07] NADIG A. S., OZONOFF S., YOUNG G. S., ROZGA A., SIGMAN M., ROGERS S. J.: A prospective study of response to name in infants at risk for autism. *Archives of Pediatrics & Adolescent Medicine 161*, 4 (Apr. 2007), 378–383. doi:10.1001/archpedi.161.4.378. 1

[PMR*96] PLAISANT C., MILASH B., ROSE A., WIDOFF S., SHNEIDERMAN B.: LifeLines: visualizing personal histories. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 1996), CHI '96, ACM, pp. 221–227. doi:10.1145/238386.238493. 2

[RAR*13] REHG J., ABOWD G., ROZGA A., ROMERO M., CLEMENTS M., SCLAROFF S., ESSA I., OUSLEY O., LI Y., KIM C., RAO H., KIM J., PRESTI L., ZHANG J., LANTSMAN D., BIDWELL J., YE Z.: Decoding children's social behavior. In *2013 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* (June 2013), pp. 3414–3421. doi:10.1109/CVPR.2013.438. 7

[RFBG01] ROBINS D. L., FEIN D., BARTON M. L., GREEN J. A.: The modified checklist for autism in toddlers: an initial study investigating the early detection of autism and pervasive developmental disorders. *Journal of Autism and Developmental Disorders 31*, 2 (Apr. 2001), 131–144. 1, 5, 7

[SMM12] SEDLMAIR M., MEYER M., MUNZNER T.: Design study methodology: Reflections from the trenches and the stacks. *IEEE Transactions on Visualization and Computer Graphics 18*, 12 (Dec. 2012), 2431–2440. doi:10.1109/TVCG.2012.213. 5

[Tov08] TOVÉE M. J.: *An introduction to the visual system*. Cambridge University Press, 2008. 2

[VWD04] VIÉGAS F. B., WATTENBERG M., DAVE K.: Studying cooperation and conflict between authors with history flow visualizations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2004), CHI '04, ACM, pp. 575–582. doi:10.1145/985692.985765. 2

[WAC*02] WETHERBY A. M., ALLEN L., CLEARY J., KUBLIN K., GOLDSTEIN H.: Validity and reliability of the communication and symbolic behavior scales developmental profile with very young children. *Journal of speech, language, and hearing research: JSLHR 45*, 6 (Dec. 2002), 1202–1218. 1, 7

[WG12] WONGSUPHASAWAT K., GOTZ D.: Exploring flow, factors, and outcomes of temporal event sequences with the outflow visualization. *IEEE Transactions on Visualization and Computer Graphics 18*, 12 (Dec. 2012), 2659–2668. doi:10.1109/TVCG.2012.225. 2

[WGGP*11] WONGSUPHASAWAT K., GUERRA GÃŞMEZ J. A., PLAISANT C., WANG T. D., TAIEB-MAIMON M., SHNEIDERMAN B.: LifeFlow: visualizing an overview of event sequences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2011), CHI '11, ACM, pp. 1747–1756. doi:10.1145/1978942.1979196. 2

[WPS*09] WANG T. D., PLAISANT C., SHNEIDERMAN B., SPRING N., ROSEMAN D., MARCHAND G., MUKHERJEE V., SMITH M.: Temporal summaries: Supporting temporal categorical searching, aggregation and comparison. *IEEE Transactions on Visualization and Computer Graphics 15*, 6 (2009), 1049–1056. doi:10.1109/TVCG.2009.187. 2