Quantifying Joint Activities using Cross-Recurrence Block Representation

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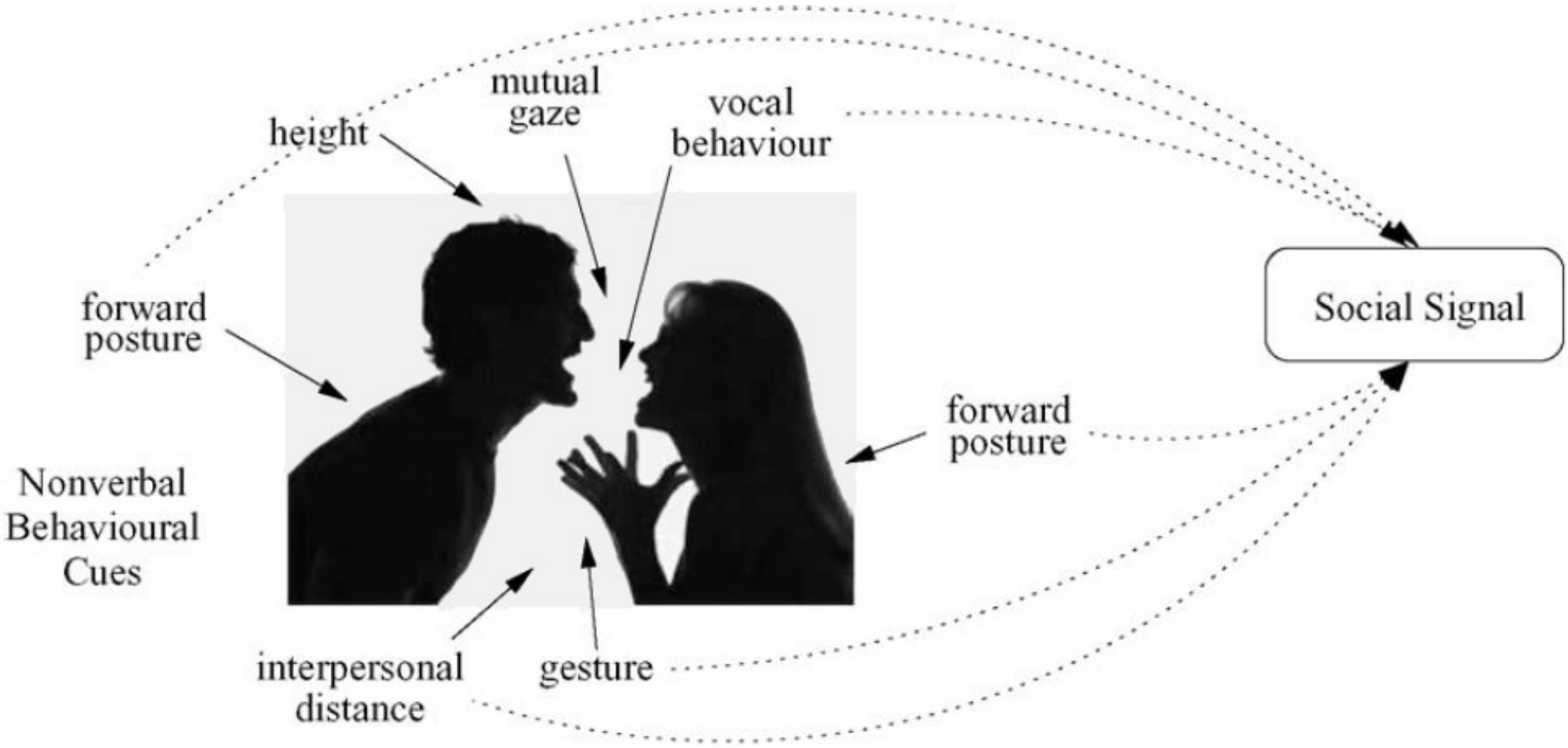
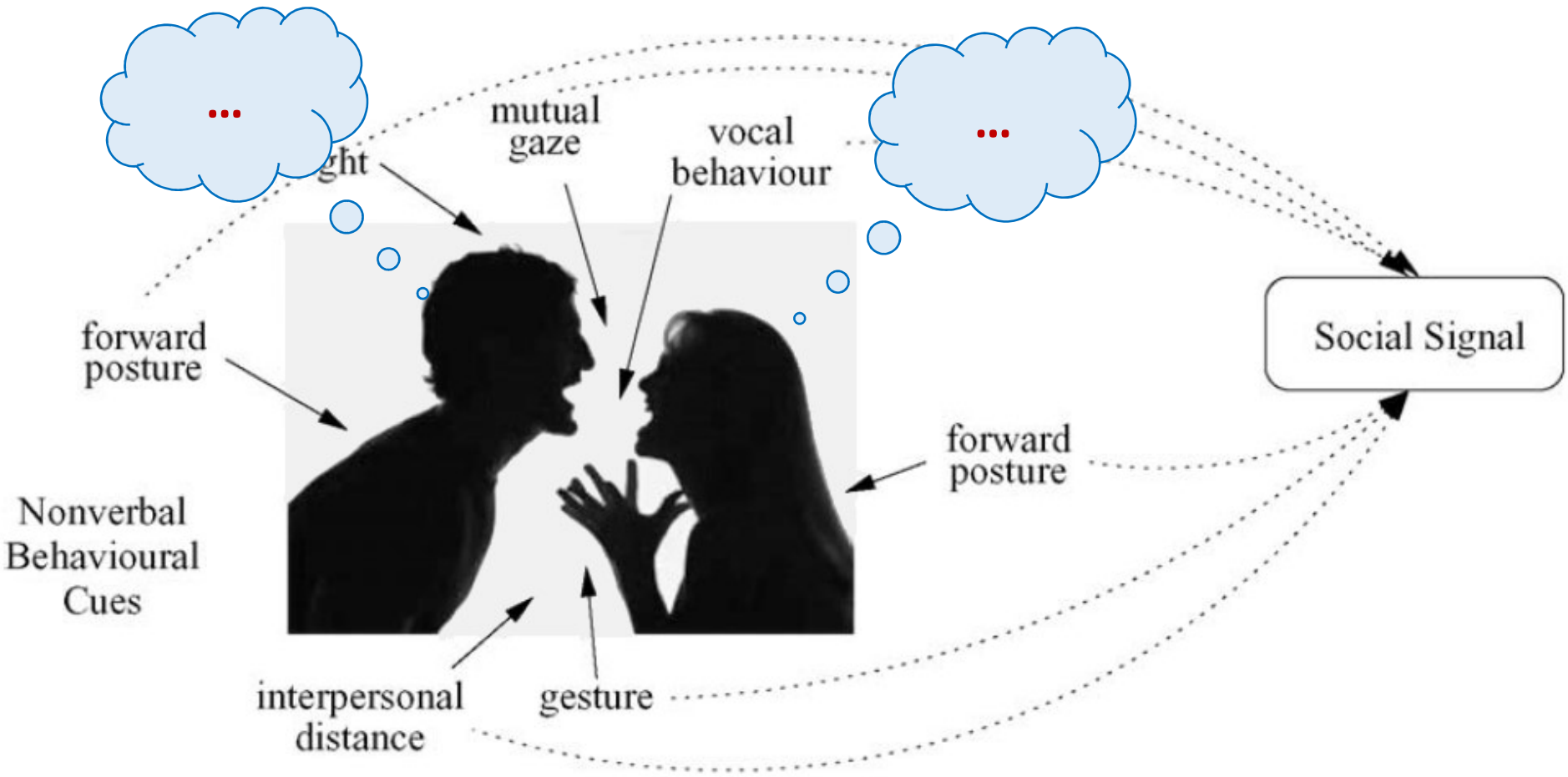
Human beings are social creatures

(Adolph, 2003)



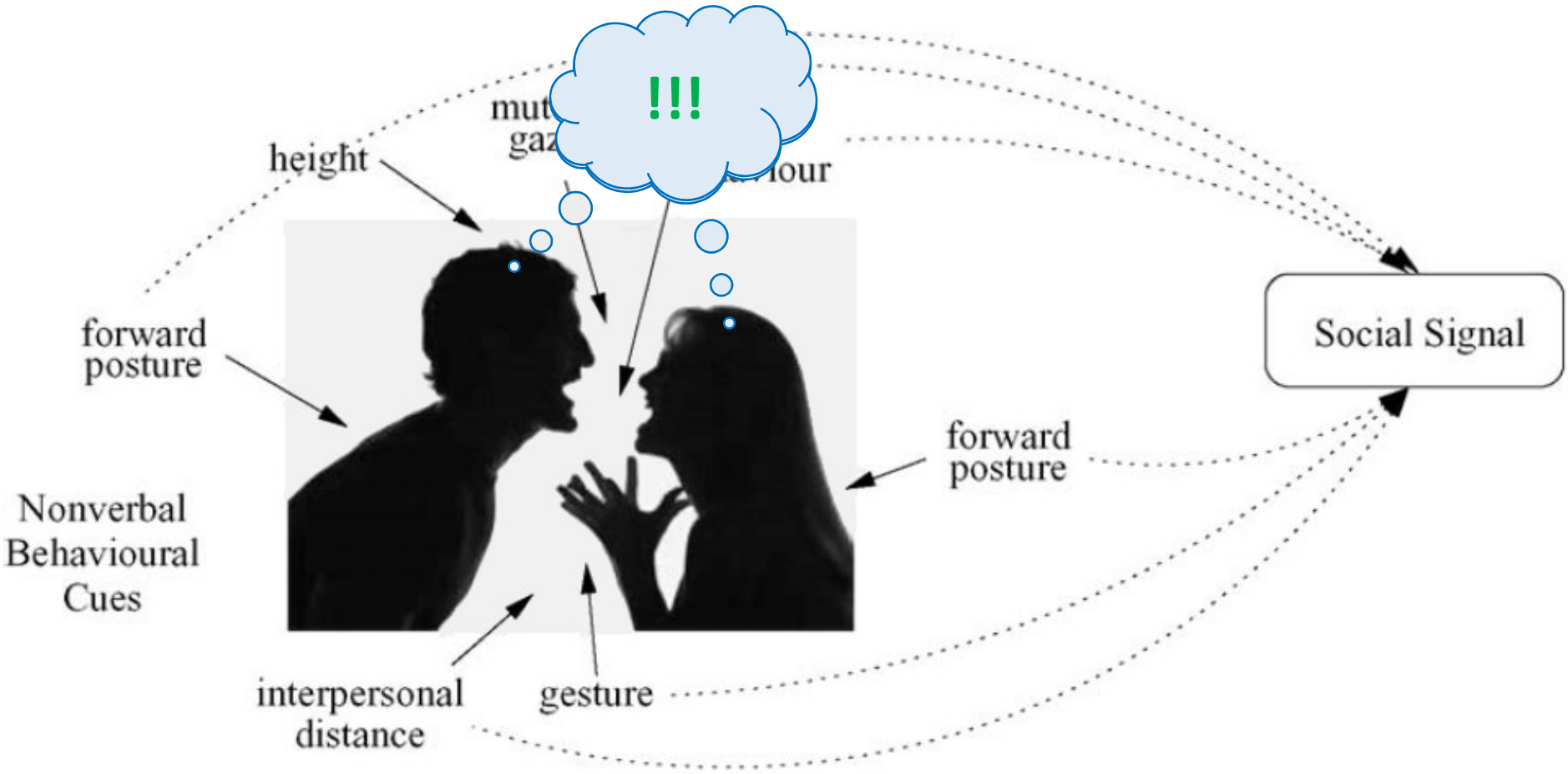
We are capable of employing various behavioral cues, such as gaze, speech, manual action, body posture in everyday communication.

(Vinciarelli, Pantic and Bourlard, 2009)



We exhibit a remarkable ability to coordinate our behaviors and engage in various joint activities with other social partners to achieve common goals.

(Kimmel, 2012; Fusaroli and Tylén, 2015)



Such mental alignment has to arise from joint activities on low level behavioral cues

(Vinciarelli, 2009)

- Social interaction is complex and non-stationary (Fusaroli et al., 2014)
  - Multi-agent, multi-modal behavioral channels with real-time feedback loop

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  - Multi-agent, multi-modal behavioral channels with real-time feedback loop
  - Evolves through different stages with time
  - Complementary coordinative structures beyond synchrony

- Technological advances in sensing and computing devices allow us to collect high-density and large volume behavioral data. (Dale, Warlaumont and Richardson, 2011; Yu, Yurovsky and Xu, 2012)

- How we can effectively discover novel and reliable patterns to advance our understanding of human interaction and coordinated behaviors?

- Technological advances in sensing and computing devices allow us to collect high-density and large volume behavioral data. (Dale, Warlaumont and Richardson, 2011; Yu, Yurovsky and Xu, 2012)

- How we can effectively discover novel and reliable patterns to advance our understanding of human interaction and coordinated behaviors?

A new analysis method to quantify engagement and joint activities in social interaction based on

Cross Recurrence Plot (CRP)

Outline

1. Explain Cross Recurrence Plot (CRP) with our empirical data set collected from a child-parent toy-play interaction experiment.

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Outline

1. Explain Cross Recurrence Plot (CRP) with our empirical data set collected from a child-parent toy-play interaction experiment.
2. Propose a new underlying data structure for CRP: **Cross Recurrence Block** and a suite of quantitative measures that reveal fine-grained coordinative patterns.
3. How this new representation allows CRP to capture shared interactive dynamics with more than two behavioral modules or agents.

Cross Recurrence Plot

- Cross-Recurrence Plot (CRP) is an extension of Recurrence Plot as a non-linear data analysis method, which was invented in the field of theoretical physics and recently applied to cognitive science to study interpersonal coordination (Eckmann et al., 1987; Zbilut et al., 1998; Marwan et al., 2007; Fusaroli and Tylén, 2015).

Cross Recurrence Plot

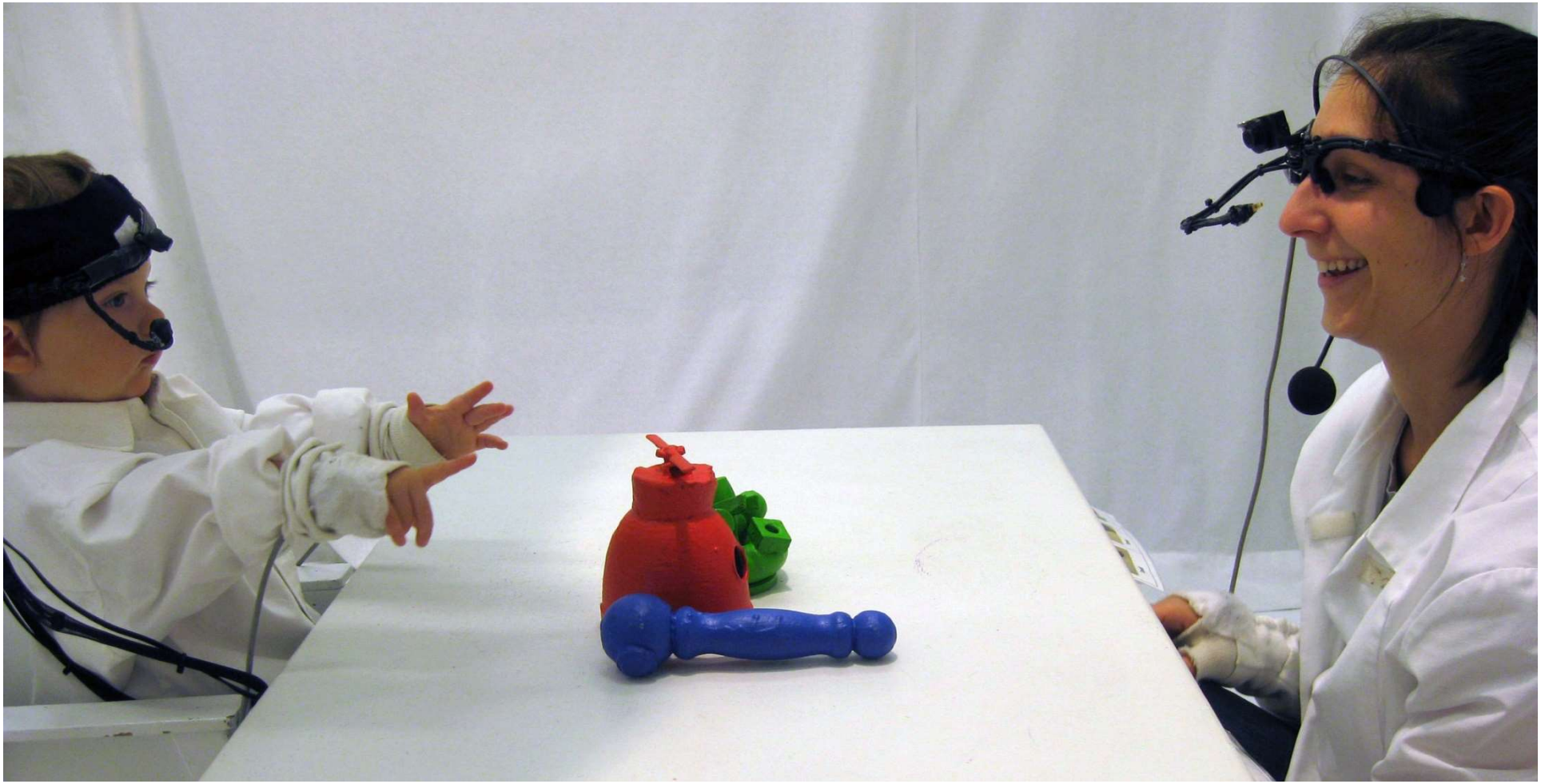
- Researchers construct Cross-Recurrence Plot (CRP) between two different time series, identify the possible state space of the two systems and when in time they co-visit similar states.

- CRP visualizes and produces quantitative indexes to describe the underlying shared dynamic trajectory between the two systems. (Coco and Dale, 2014)

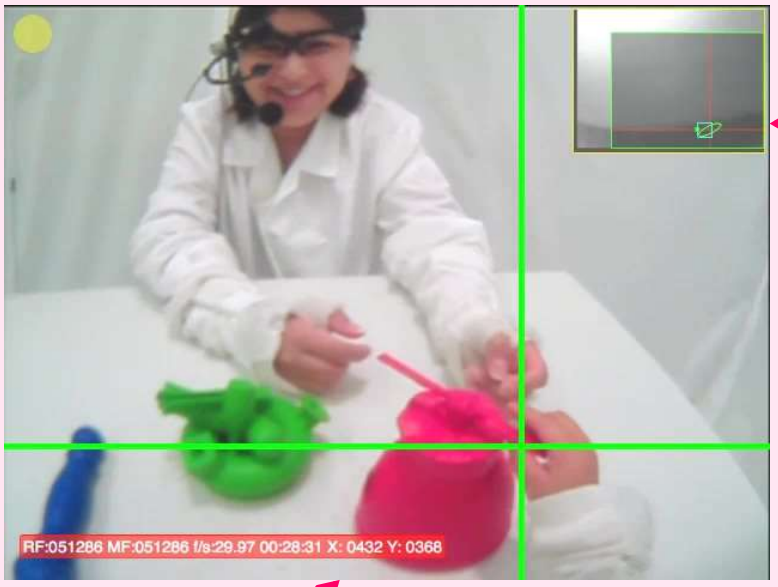
Cross Recurrence Plot

- It has been widely used in many areas
  - pattern and rhythm in sound and music (Cooper and Foote, 2002) gaze coupling between speaker and listener (Richardson & Dale, 2005)
  - linguistic pattern matching between caregivers and children (Dale and Spivey, 2005)
  - visual search scan pattern analysis (Anderson et al., 2012)
  - visual attention through eye-hand coordination during child parent interaction (Yu and Smith, 2013)
  - discourse conceptual structure analysis in doctor patient conversations (Angus et al., 2012)

Apply Cross Recurrence Plot (CRP) analysis method to a multimodal child-parent interaction data set



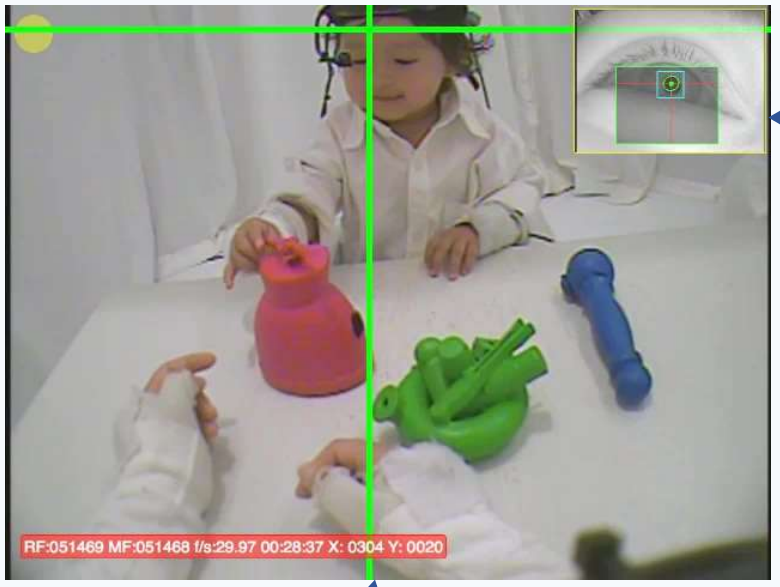
The child's first person view



From eye camera

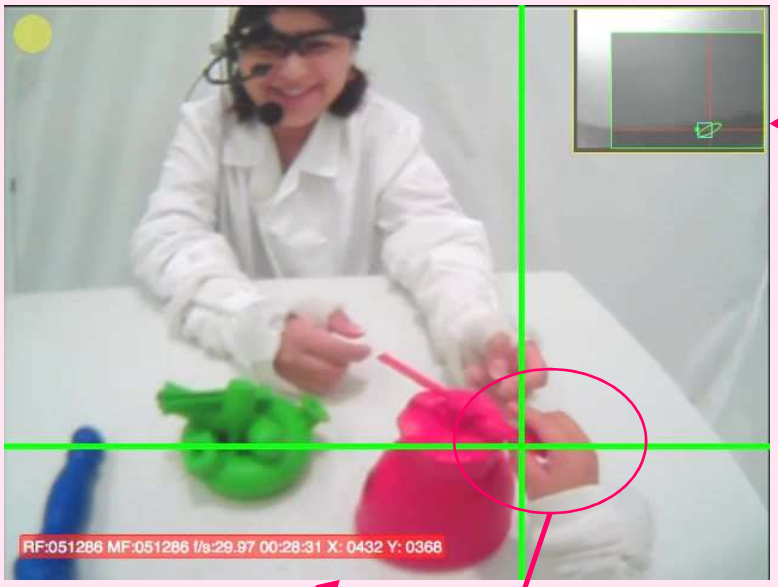
Child's eye tracker

The parent's first person view



From eye camera

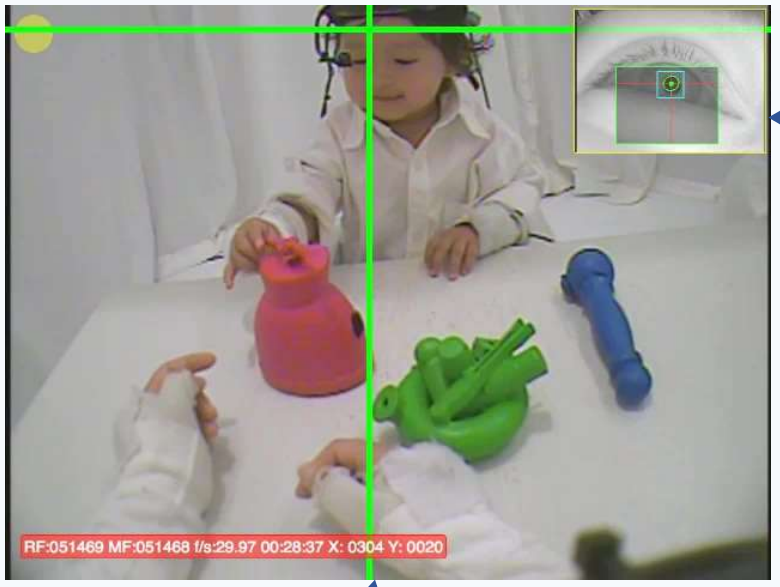
The child's first person view



From eye camera

Child's eye tracker

The parent's first person view

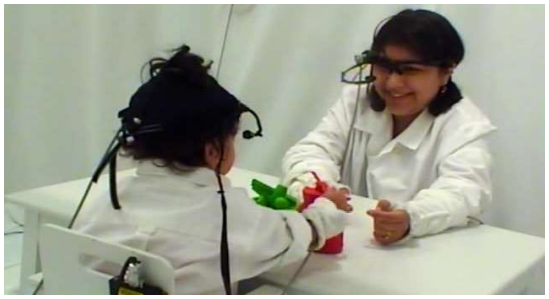


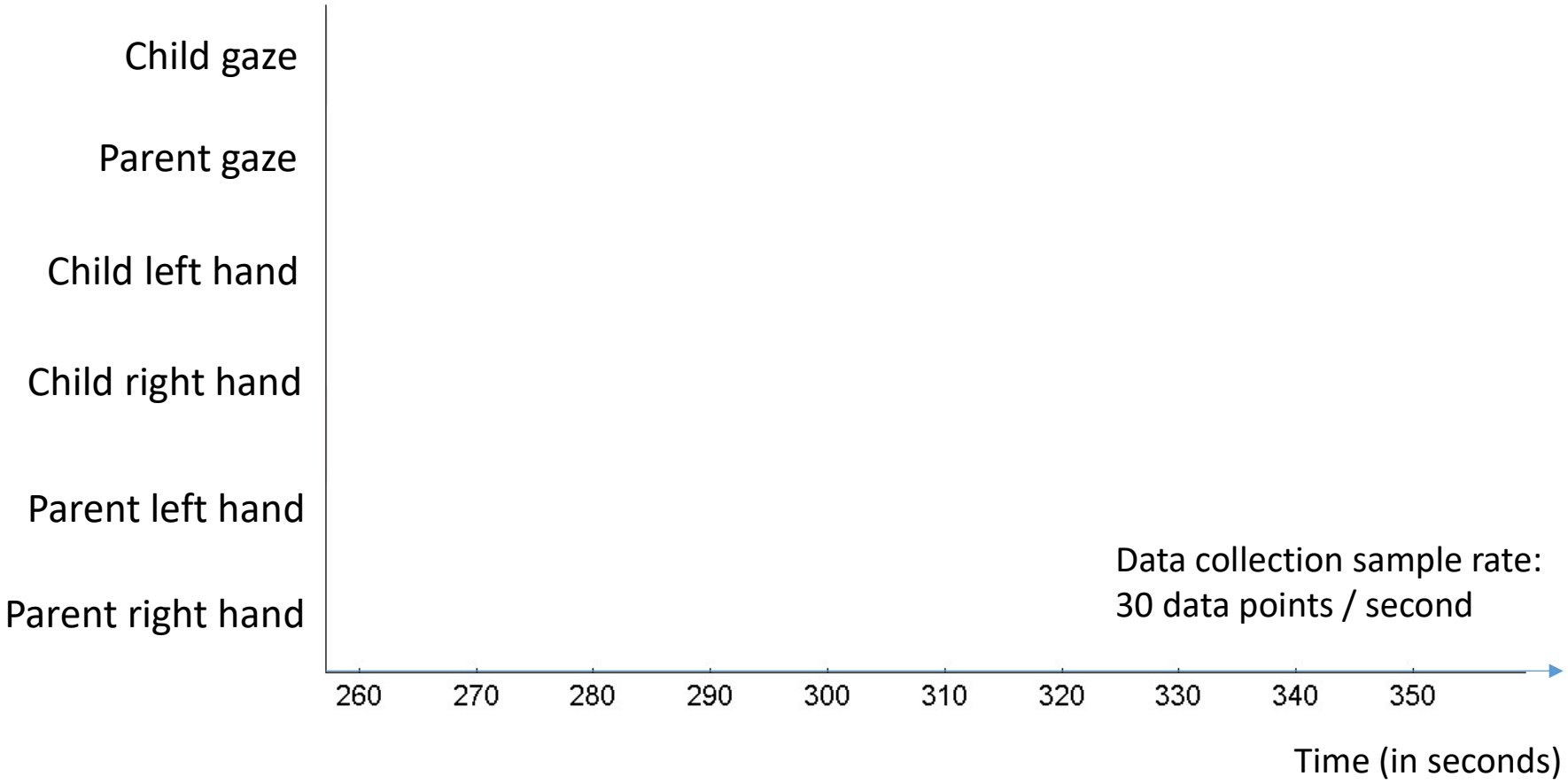
From eye camera

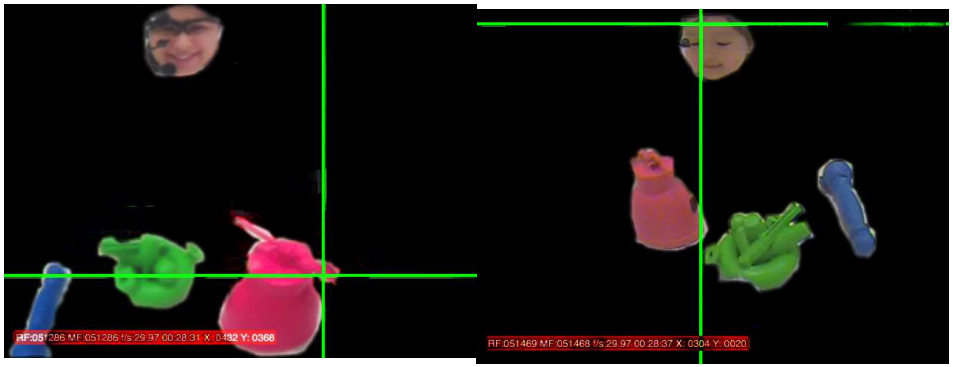
Manual coding of hand action: child right hand holding red object

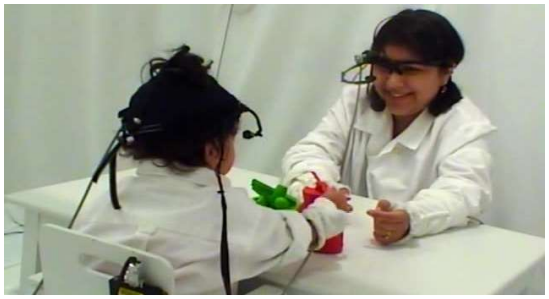
Eye gaze tracking and Region-Of-Interest (ROI) coding

Speech recording

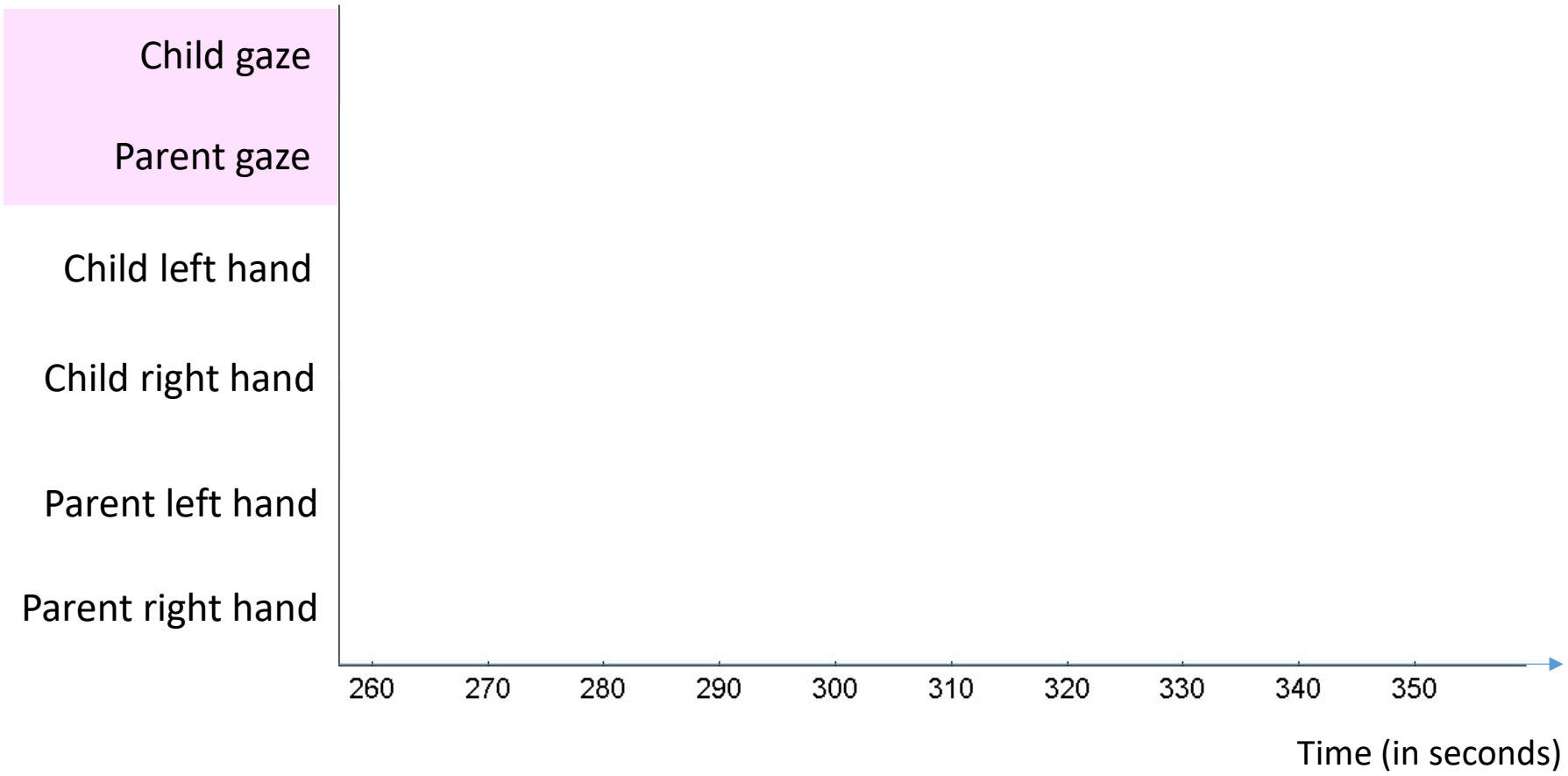


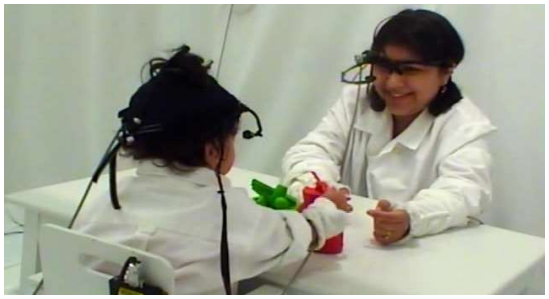

Child gaze
Parent gaze
Child left hand
Child right hand
Parent left hand
Parent right hand
Data collection sample rate:
30 data points / second
260
270
280
290
300
310
320
330
340
350
Time (in seconds)





blue object green object red object face





blue object green object red object face

Child gaze

Parent gaze

Child left hand

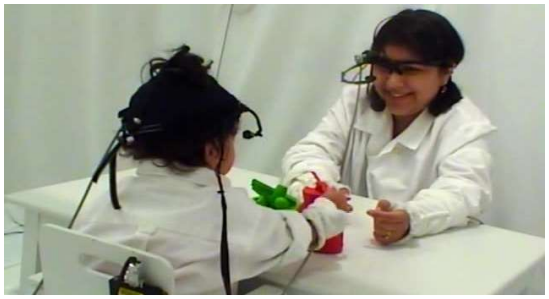
Child right hand

Parent left hand

Parent right hand

260 270 280 290 300 310 320 330 340 350

Time (in seconds)



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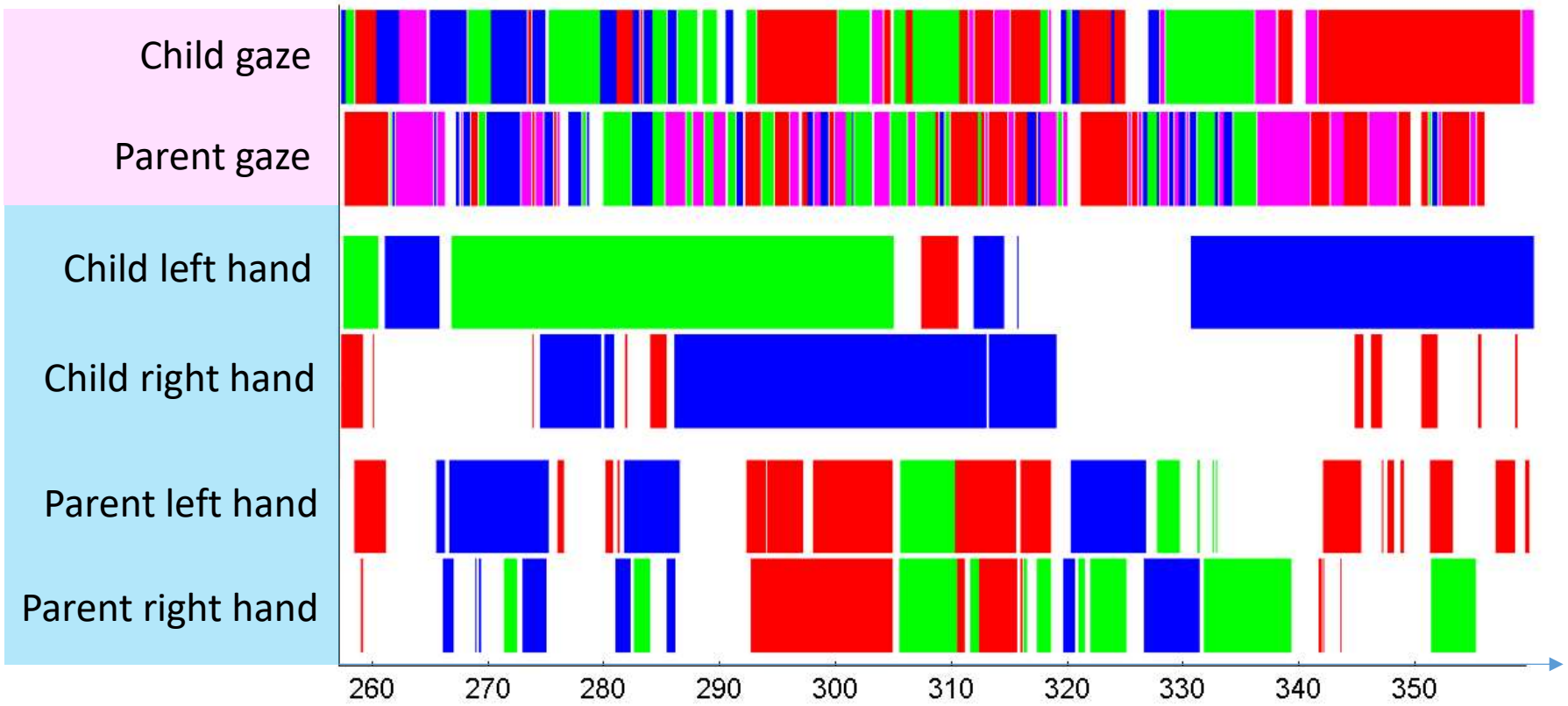
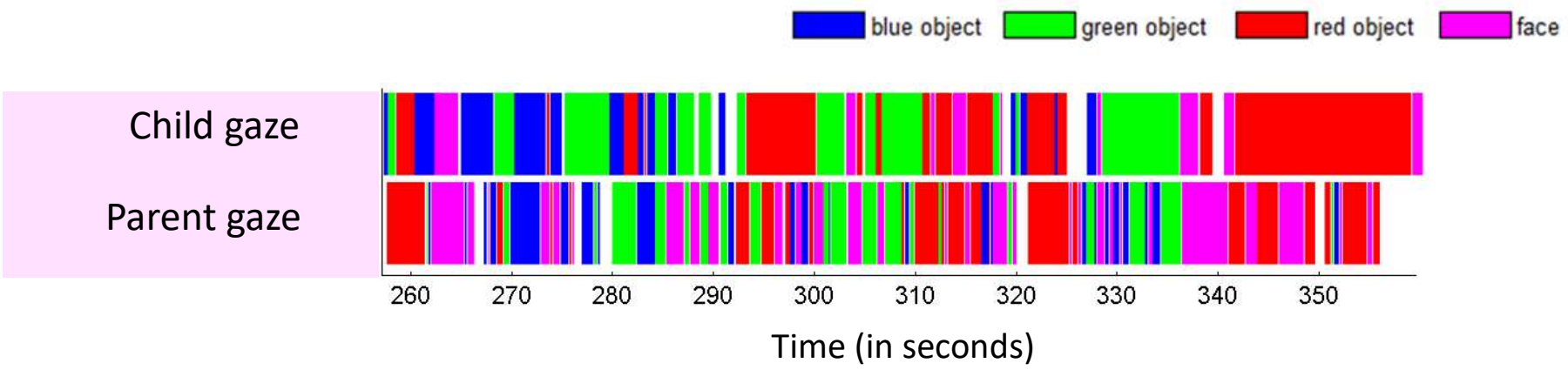
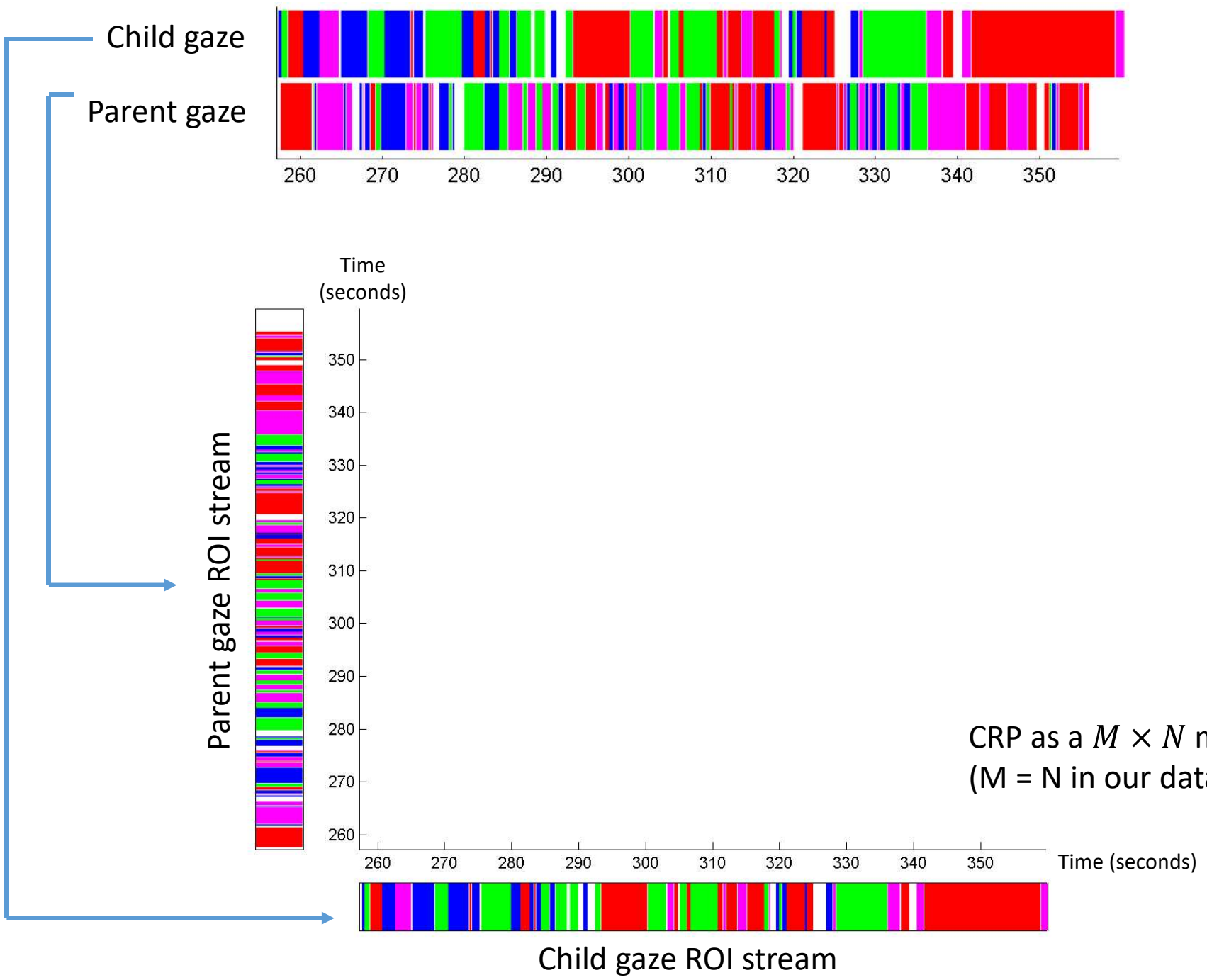
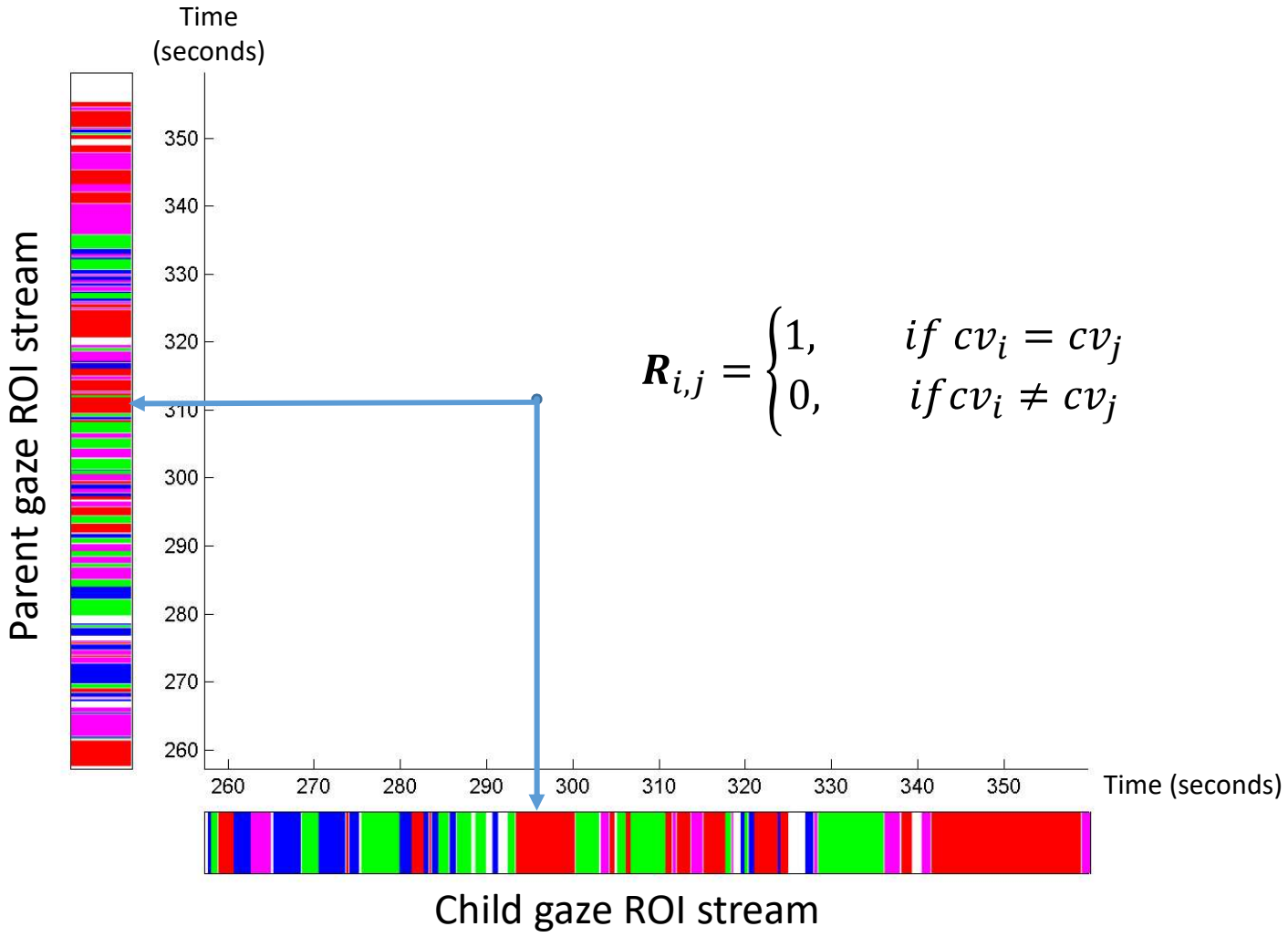




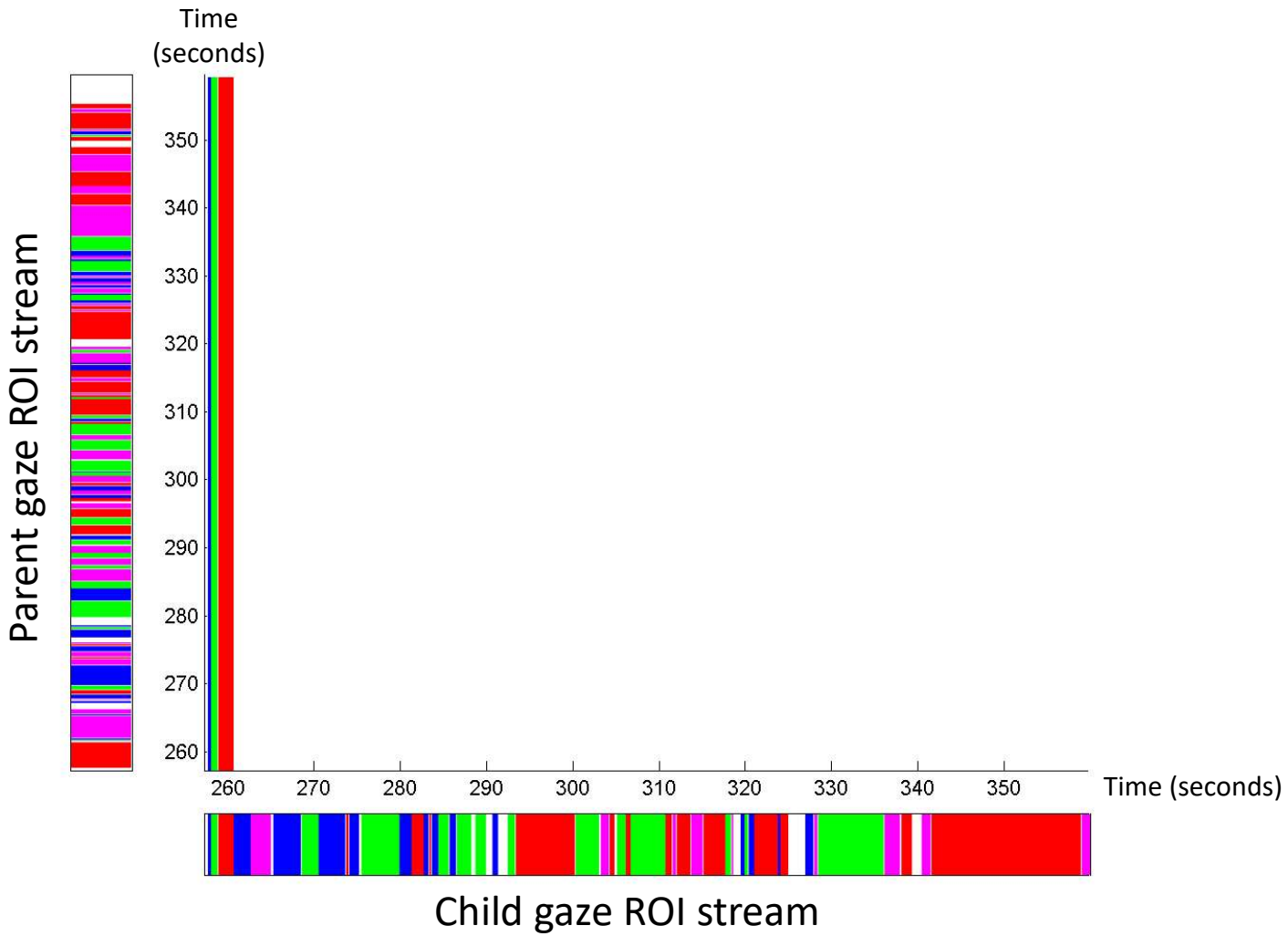
Construct Cross Recurrence Plot (CRP) using two gaze streams

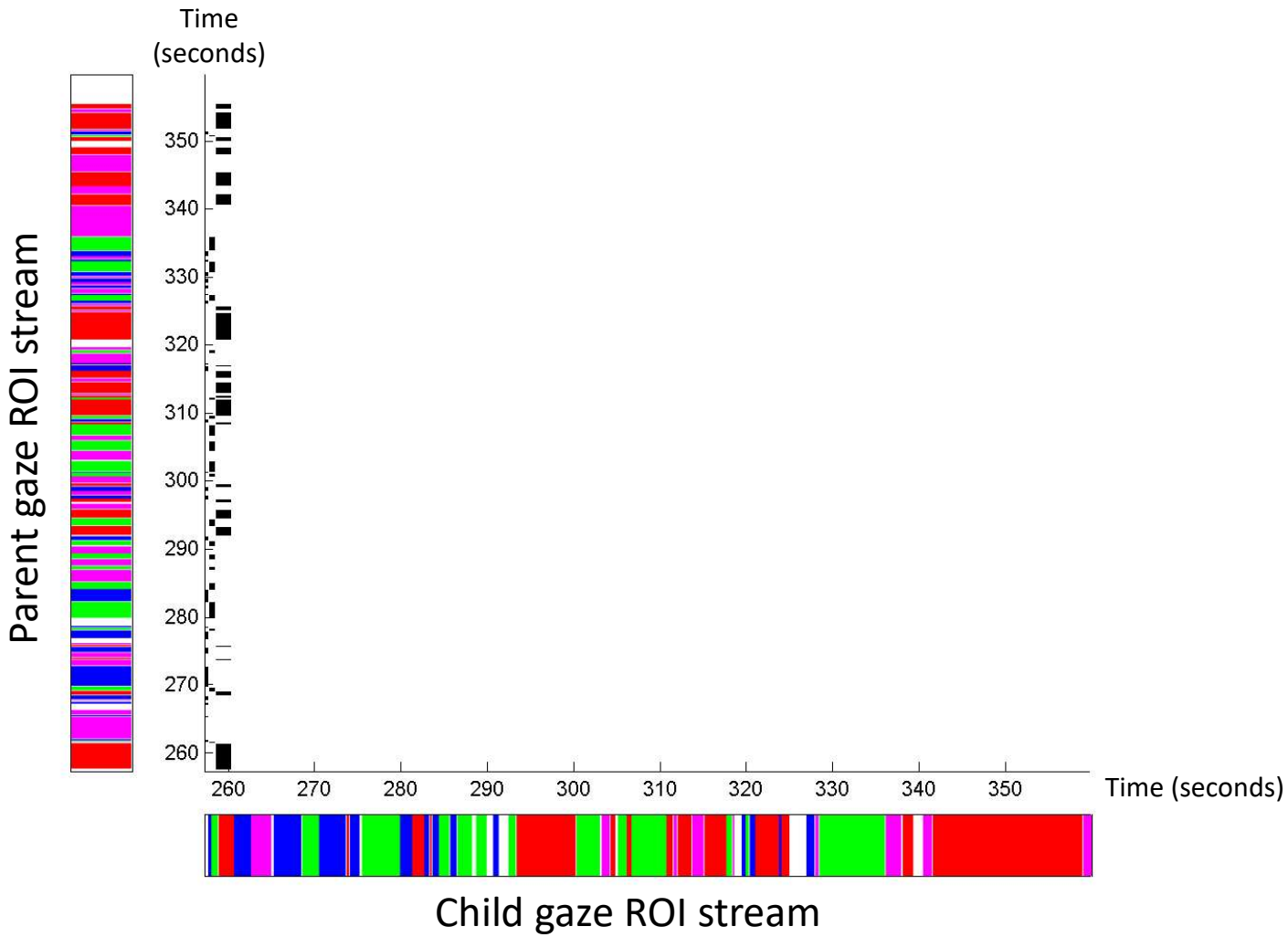

Child gaze
Parent gaze
260
270
280
290
300
310
320
330
340
350
Time
(seconds)
Parent gaze ROI stream
Time (seconds)
Child gaze ROI stream
CRP as a $M \times N$ matrix
(M = N in our data set)

Compare the categorical value (cv) at i_{th} data point of parent's gaze stream with j_{th} cv of child's gaze stream

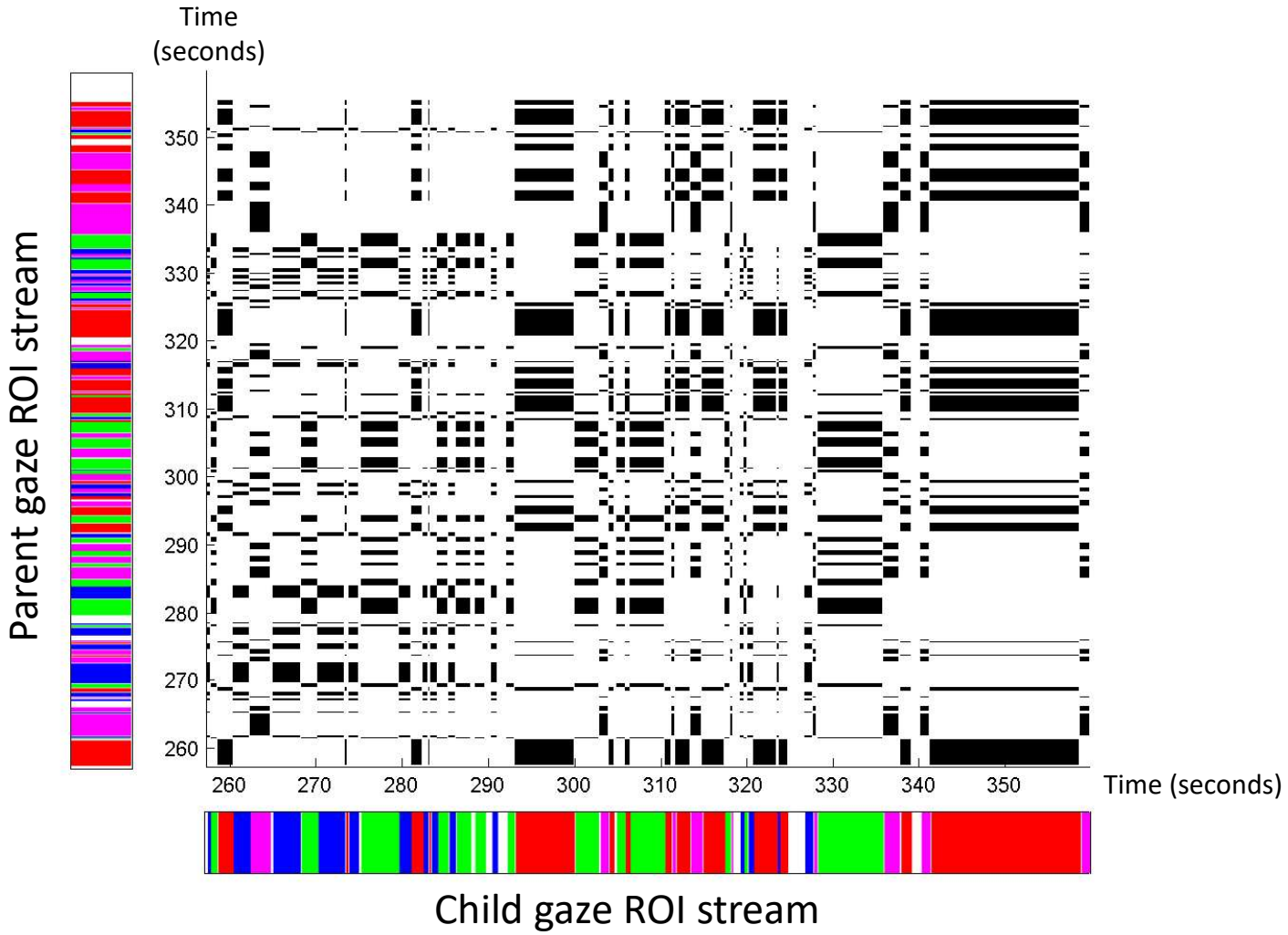


$$\boldsymbol{R}_{i,j} = \begin{cases} 1, & if\ cv_i = cv_j \\ 0, & if\ cv_i \neq cv_j \end{cases}$$

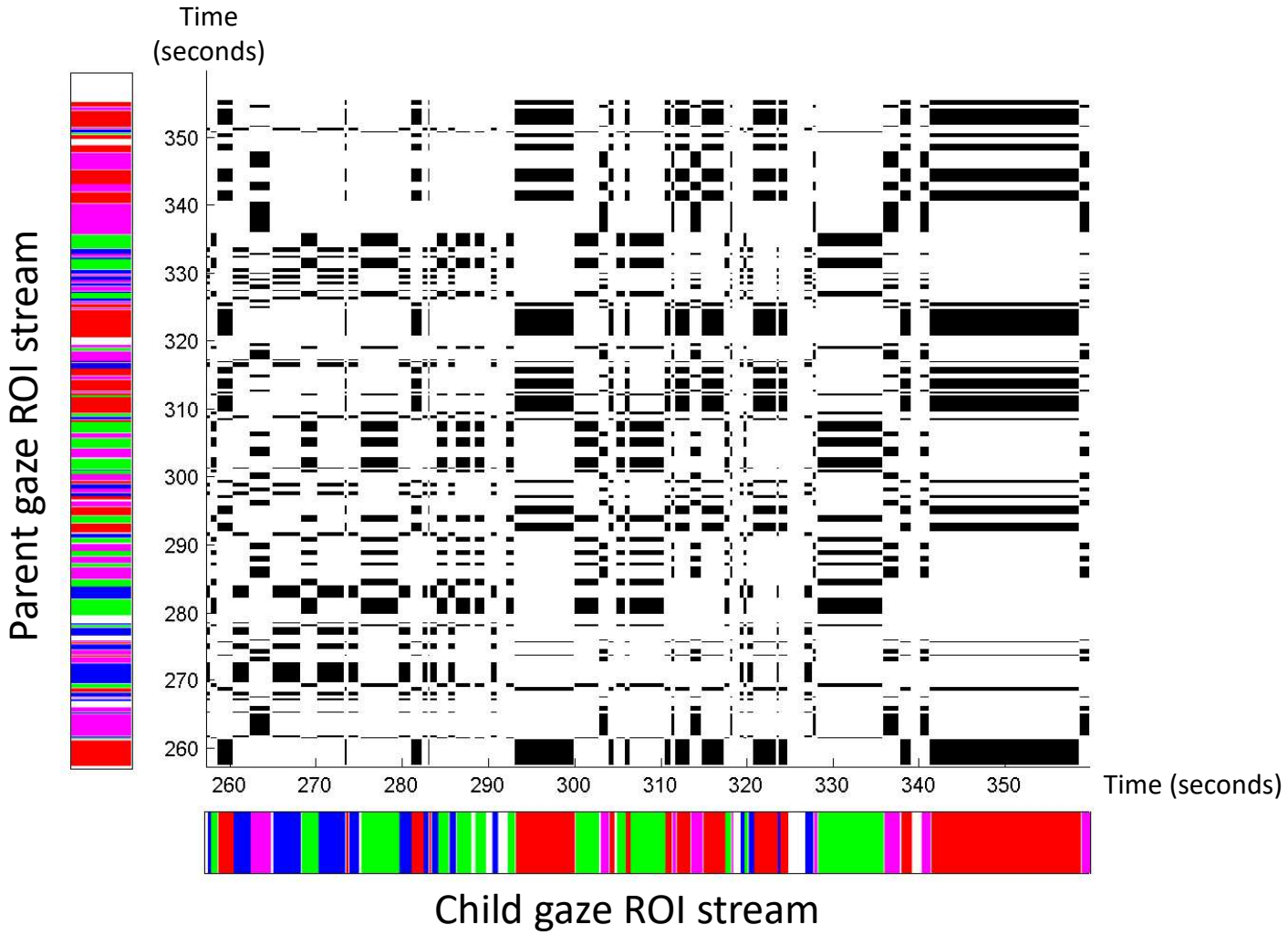

Time
(seconds)
Parent gaze ROI stream
350
340
330
320
310
300
290
280
270
260
260
270
280
290
300
310
320
330
340
350
Time (seconds)
Child gaze ROI stream


Time
(seconds)
Parent gaze ROI stream
350
340
330
320
310
300
290
280
270
260
260
270
280
290
300
310
320
330
340
350
Time (seconds)
Child gaze ROI stream

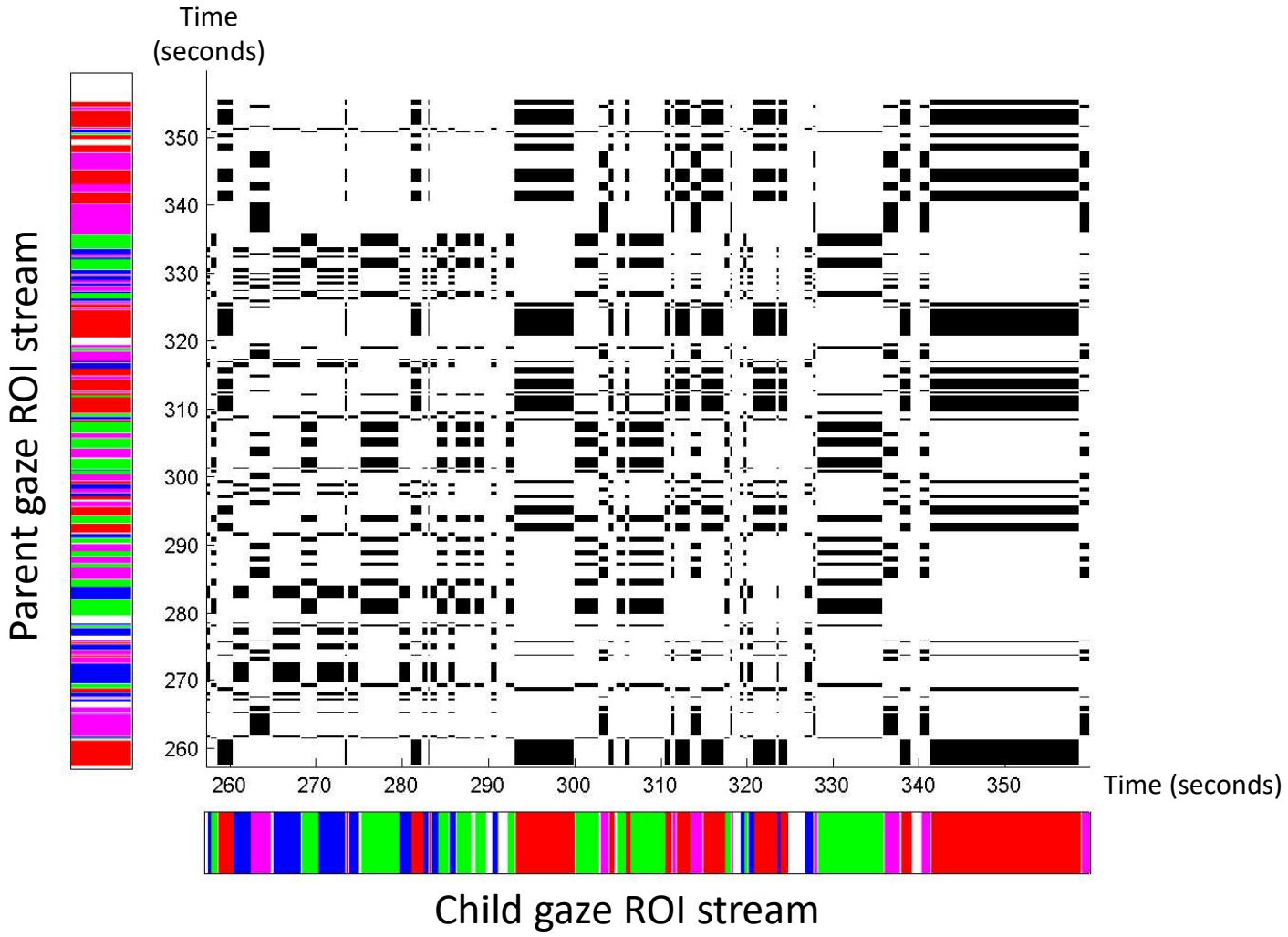
A binary matrix with black points indicating that both time series co-visited the same state with certain temporal lag.



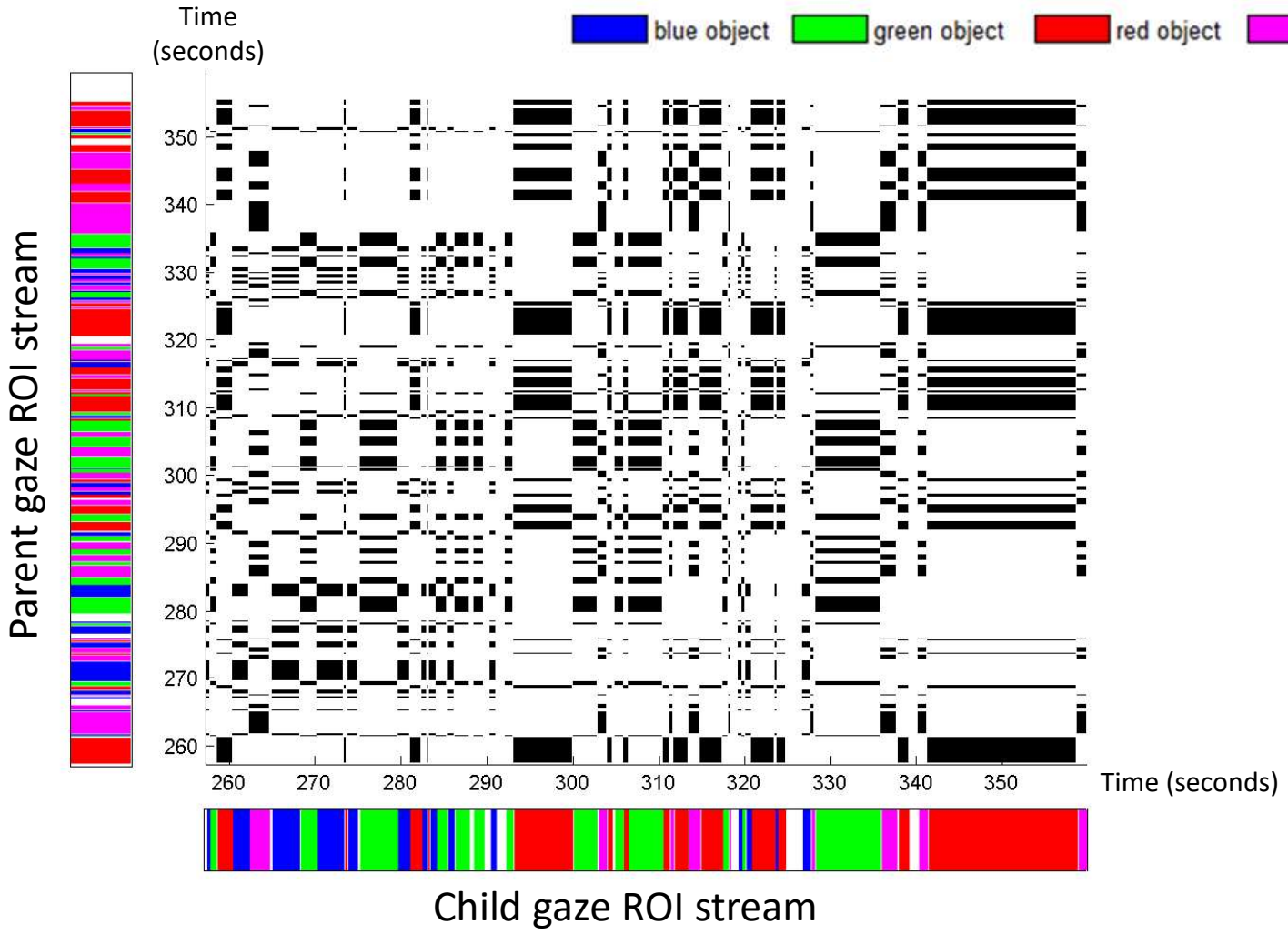
More than just match or not,
which state that both systems co-visited over time



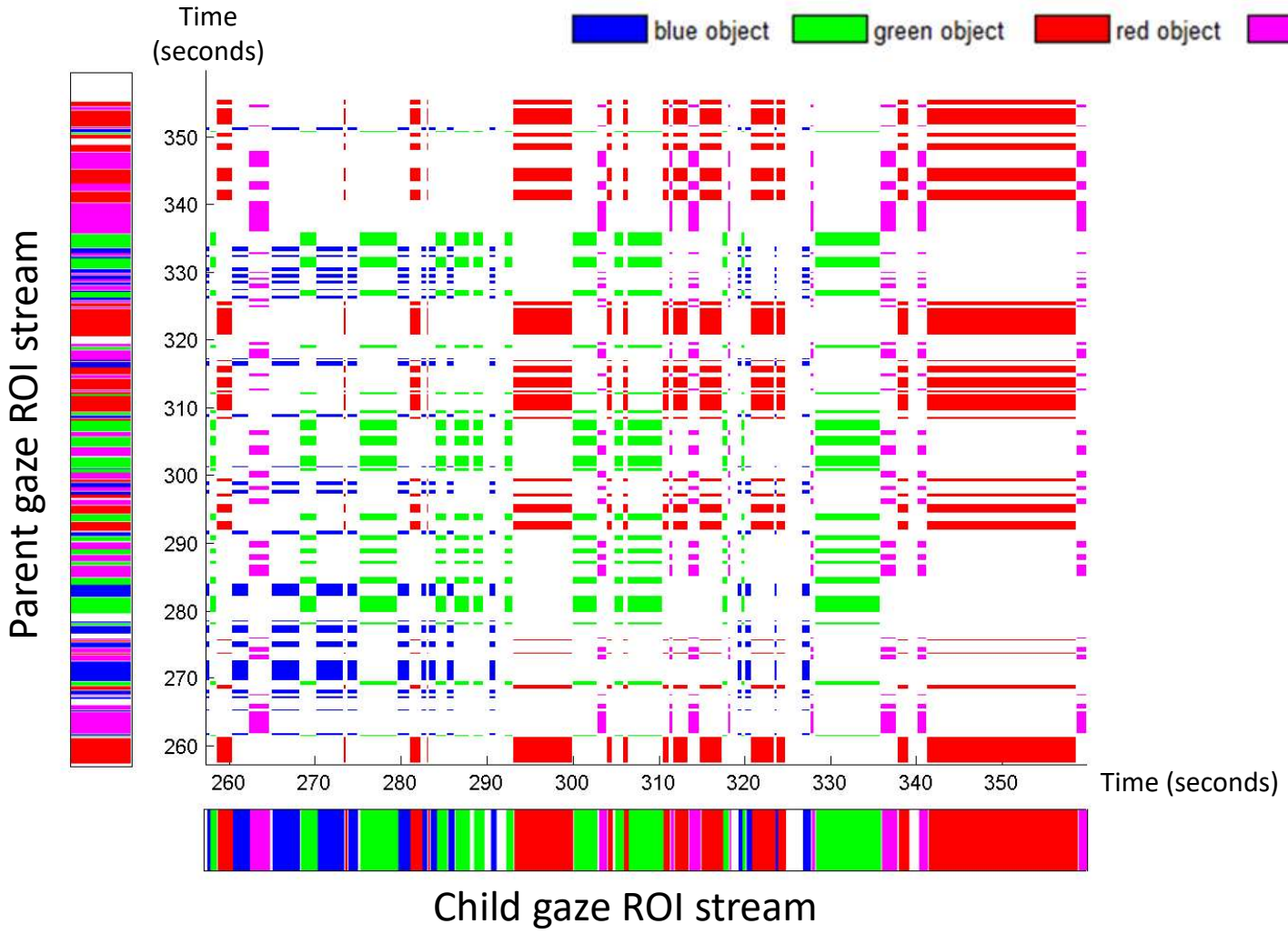
Extend the value space of $\boldsymbol{R}_{i,j}$ from $\{0, 1\}$ to include different behavioral categories.



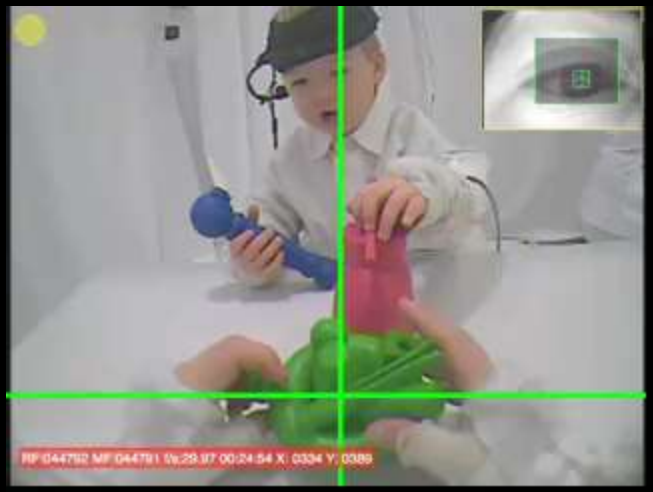
Use the four Region-Of-Interest (ROI) values as the state space for co-visitation

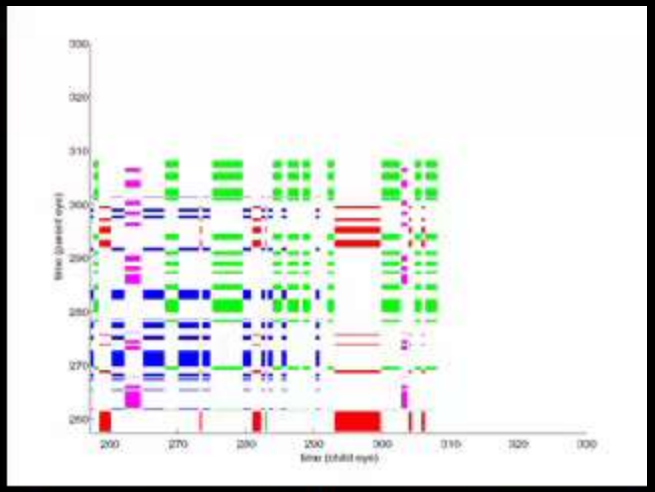


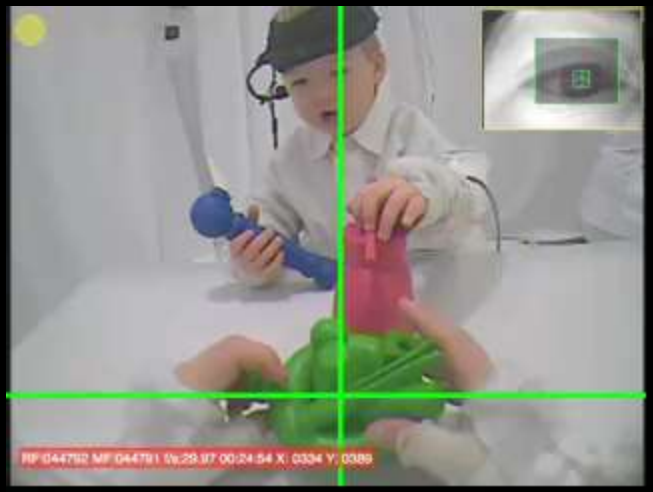
CRP is able to unfold the transition of shared interaction dynamics among different states over time.

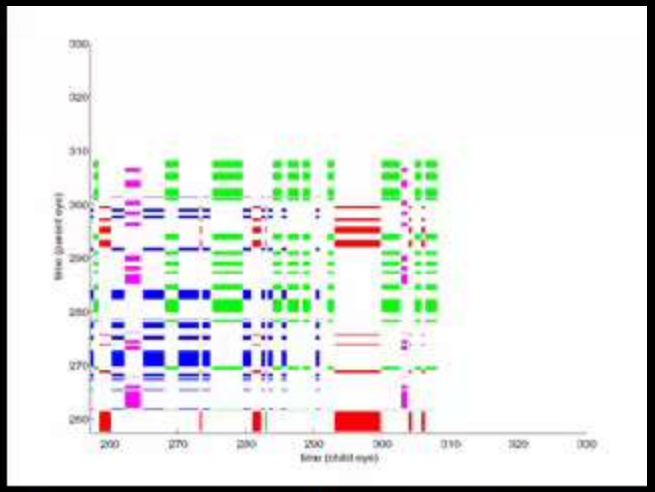


The parent’s first person view

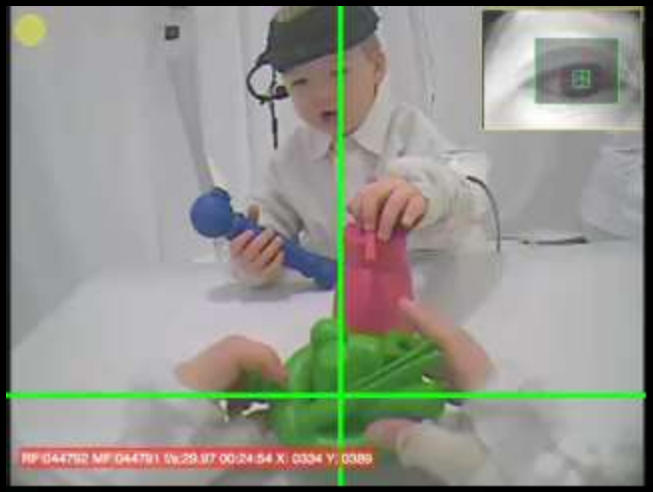


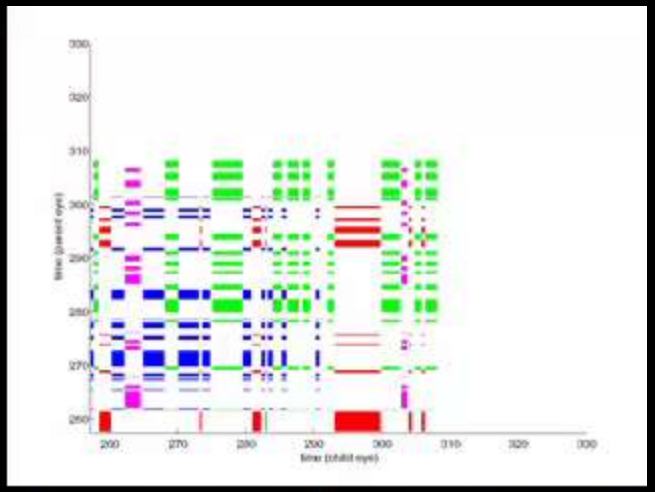


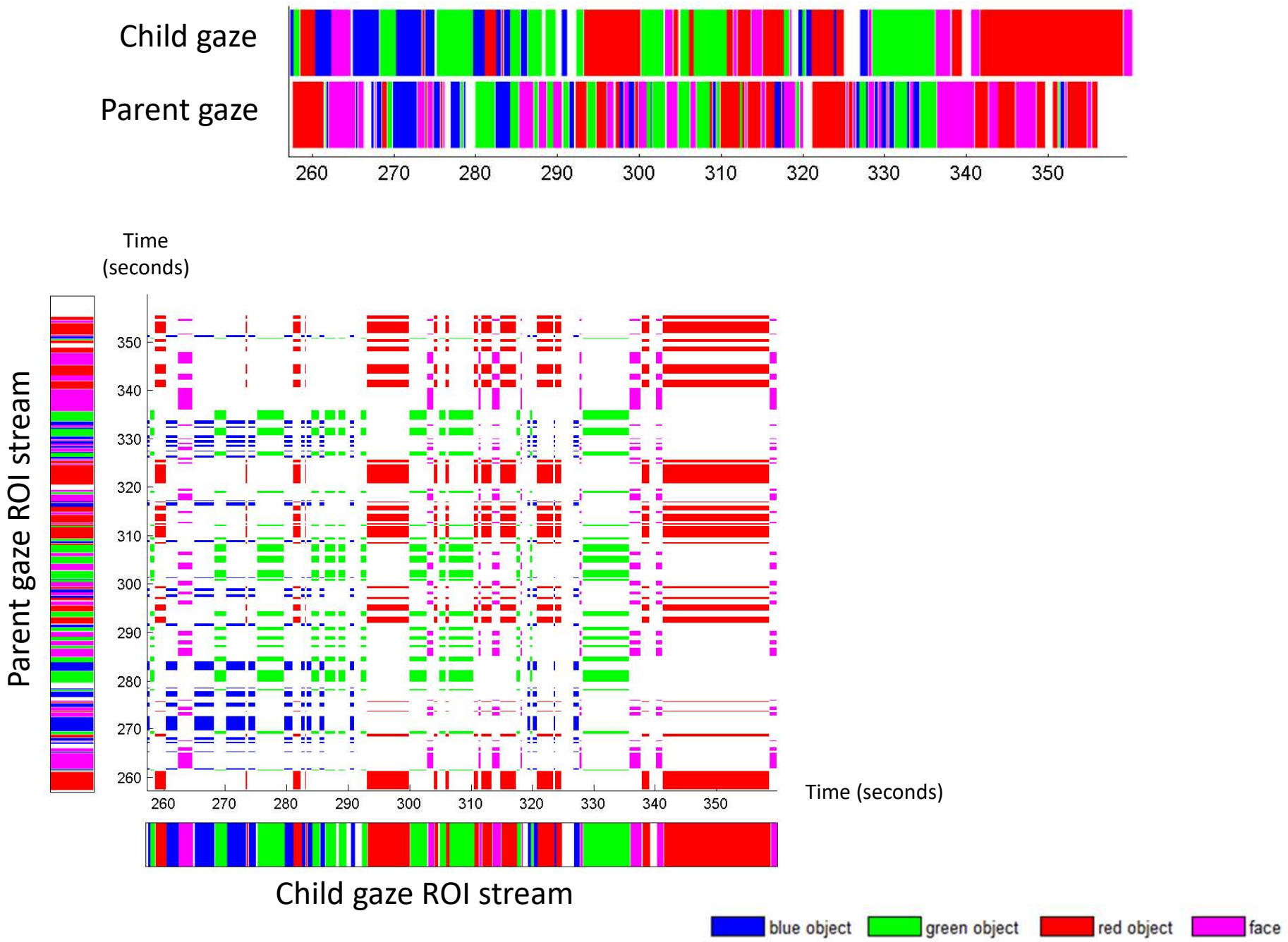


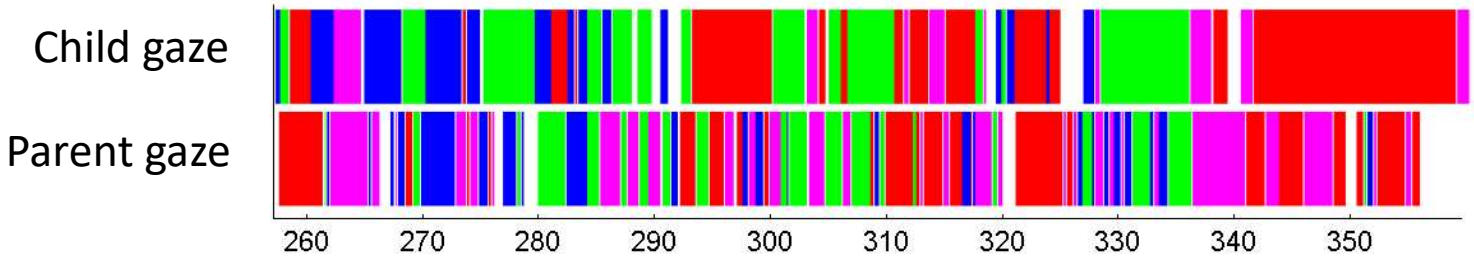


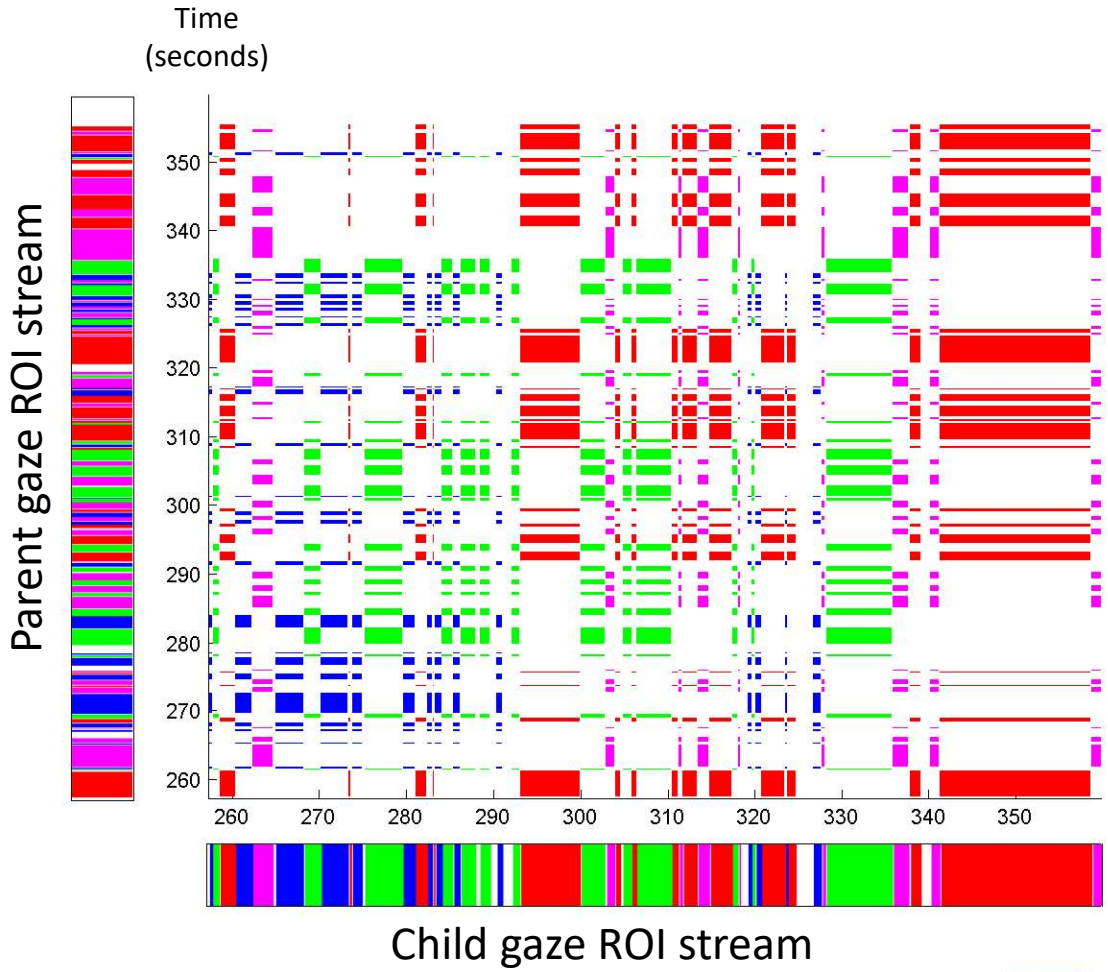
The child’s first person view




330
320
310
300
290
280
270
260
time (parent eye)
200
270
280
290
300
310
320
330
time (child eye)


Child gaze
Parent gaze
260
270
280
290
300
310
320
330
340
350
Time
(seconds)
Parent gaze ROI stream
Time (seconds)
Child gaze ROI stream
blue object
green object
red object
face

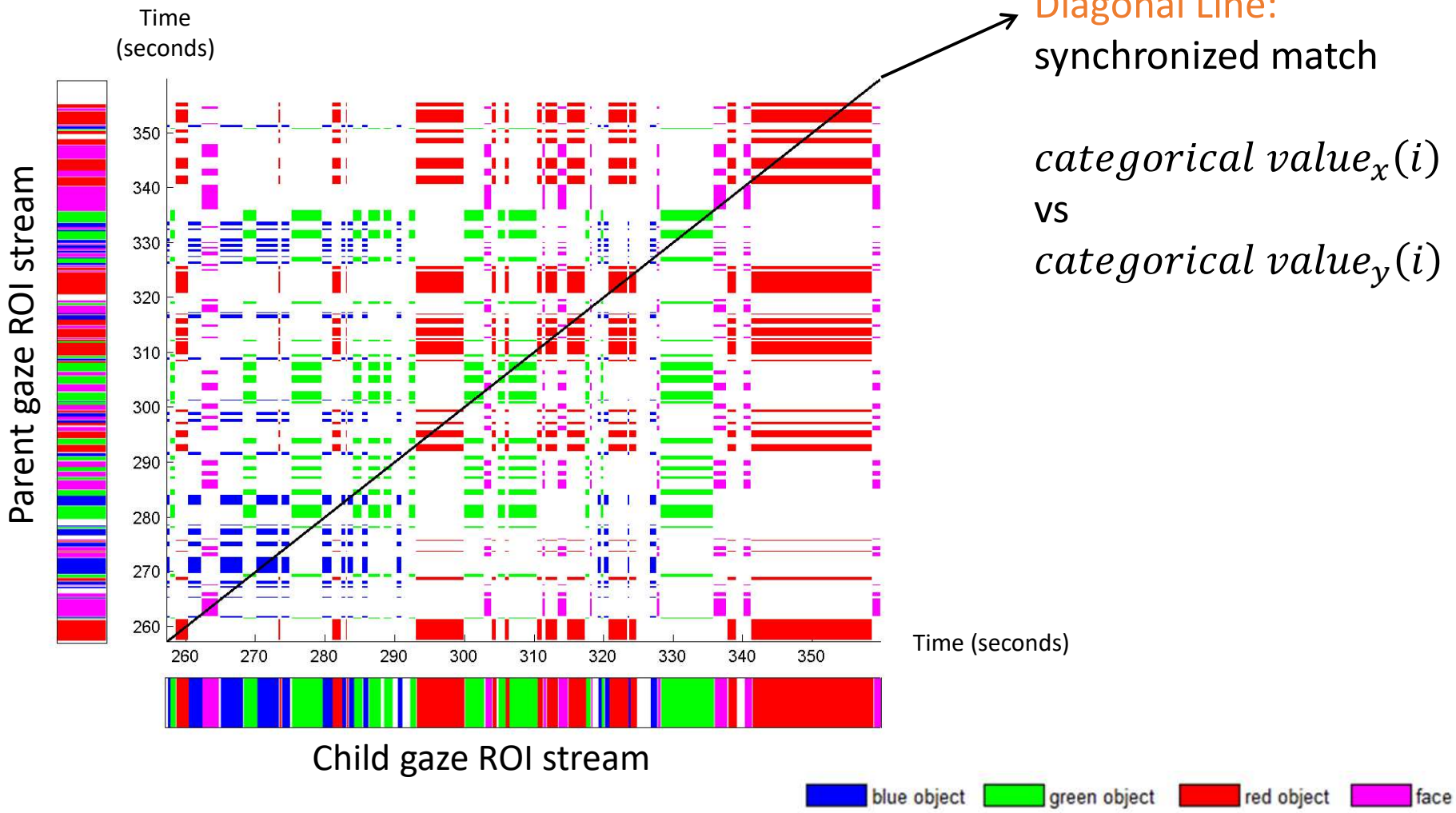


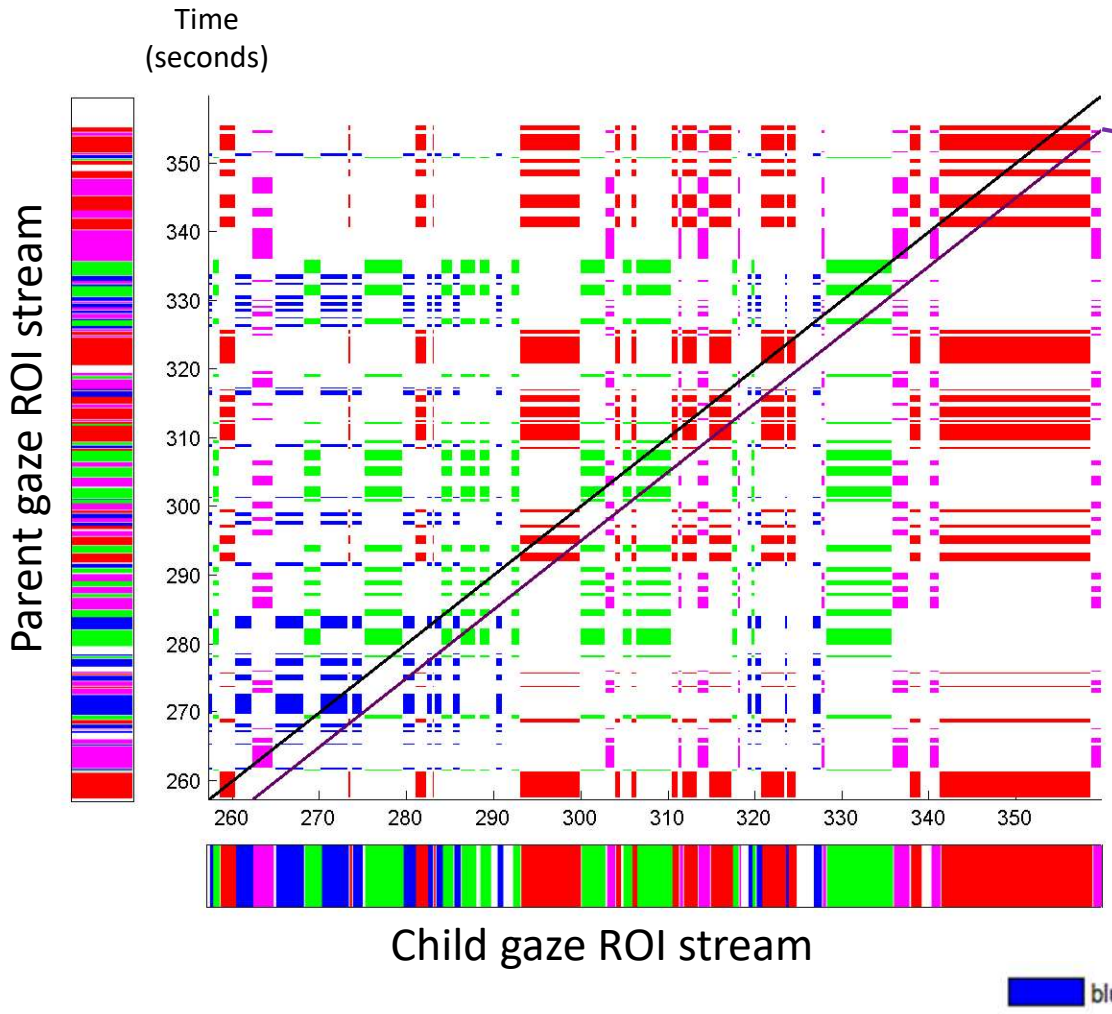


Time augmented comparison between two temporal data streams with all combinations of temporal lags.

Time (seconds)

blue object | green object | red object | face


Time
(seconds)
Parent gaze ROI stream
350
340
330
320
310
300
290
280
270
260
260
270
280
290
300
310
320
330
340
350
Time (seconds)
Child gaze ROI stream
Diagonal Line:
synchronized match
$categorical\ value_x(i)$
vs
$categorical\ value_y(i)$
blue object
green object
red object
face

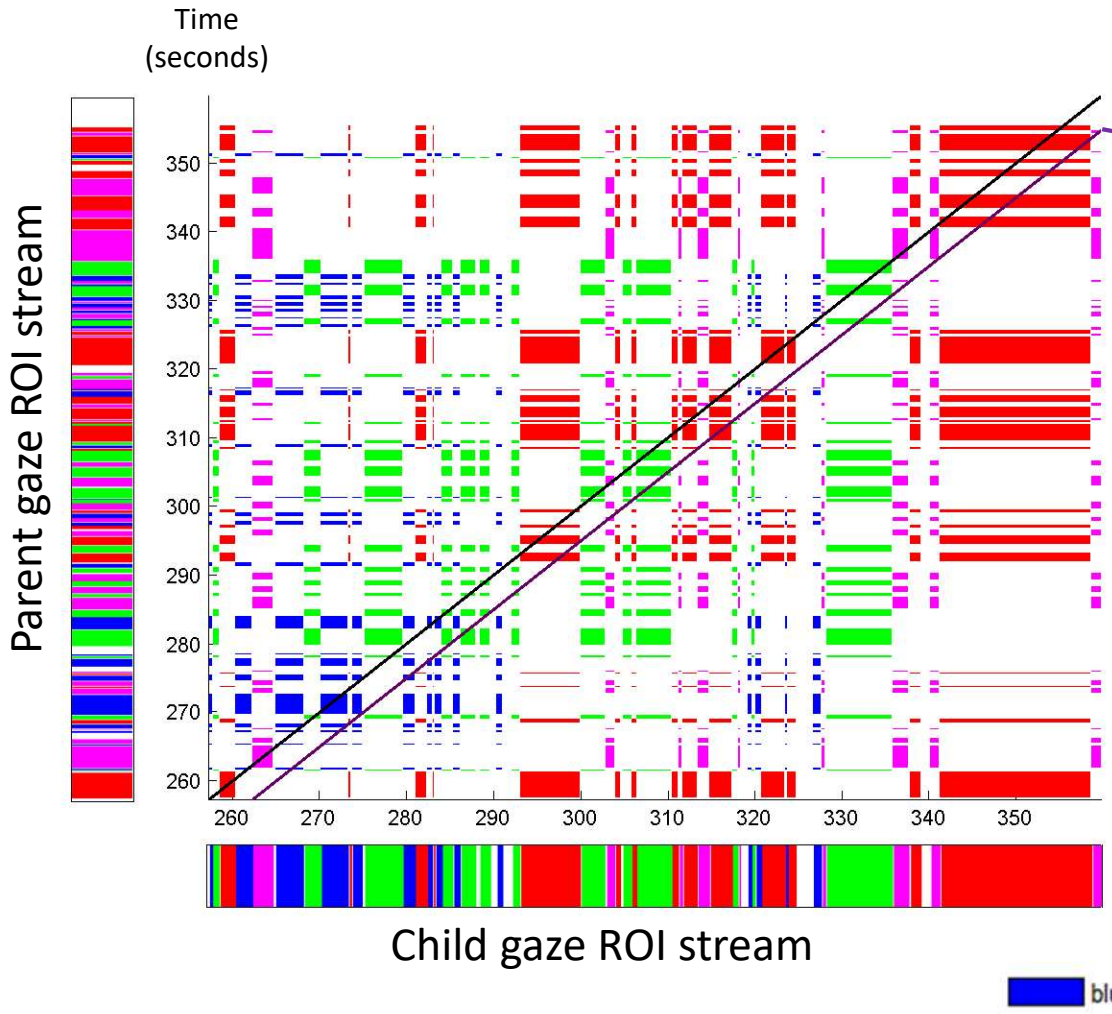


Non-Diagonal Line:
time-shifted match

$categorical\ value_x(j)$
vs
$categorical\ value_y(i)$

$i \neq j$

blue object | green object | red object | face



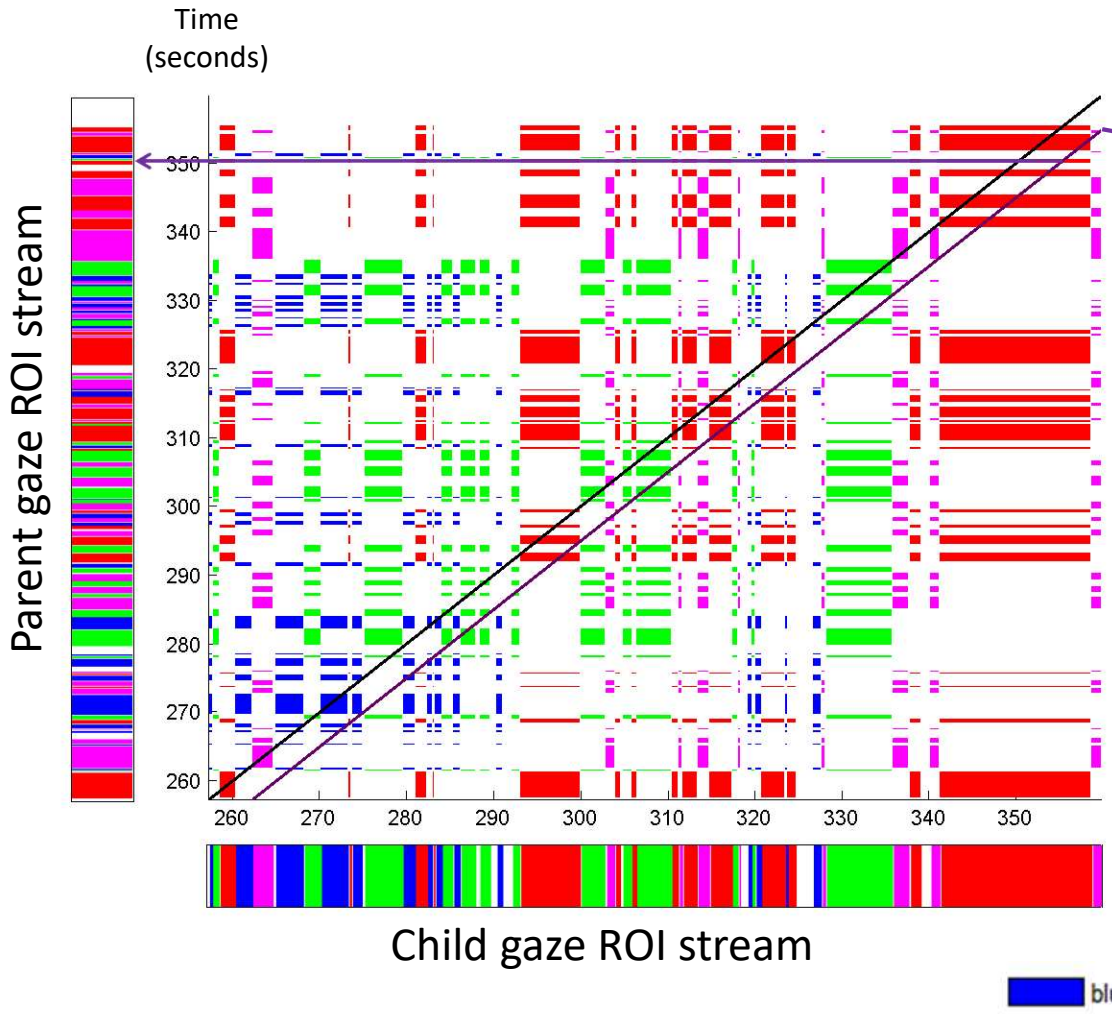
Non-Diagonal Line:
time-shifted match

$categorical\ value_x(j)$
vs
$categorical\ value_y(i)$

$j = i + 5s$

blue object | green object | red object | face

the parent's ROI at 350s



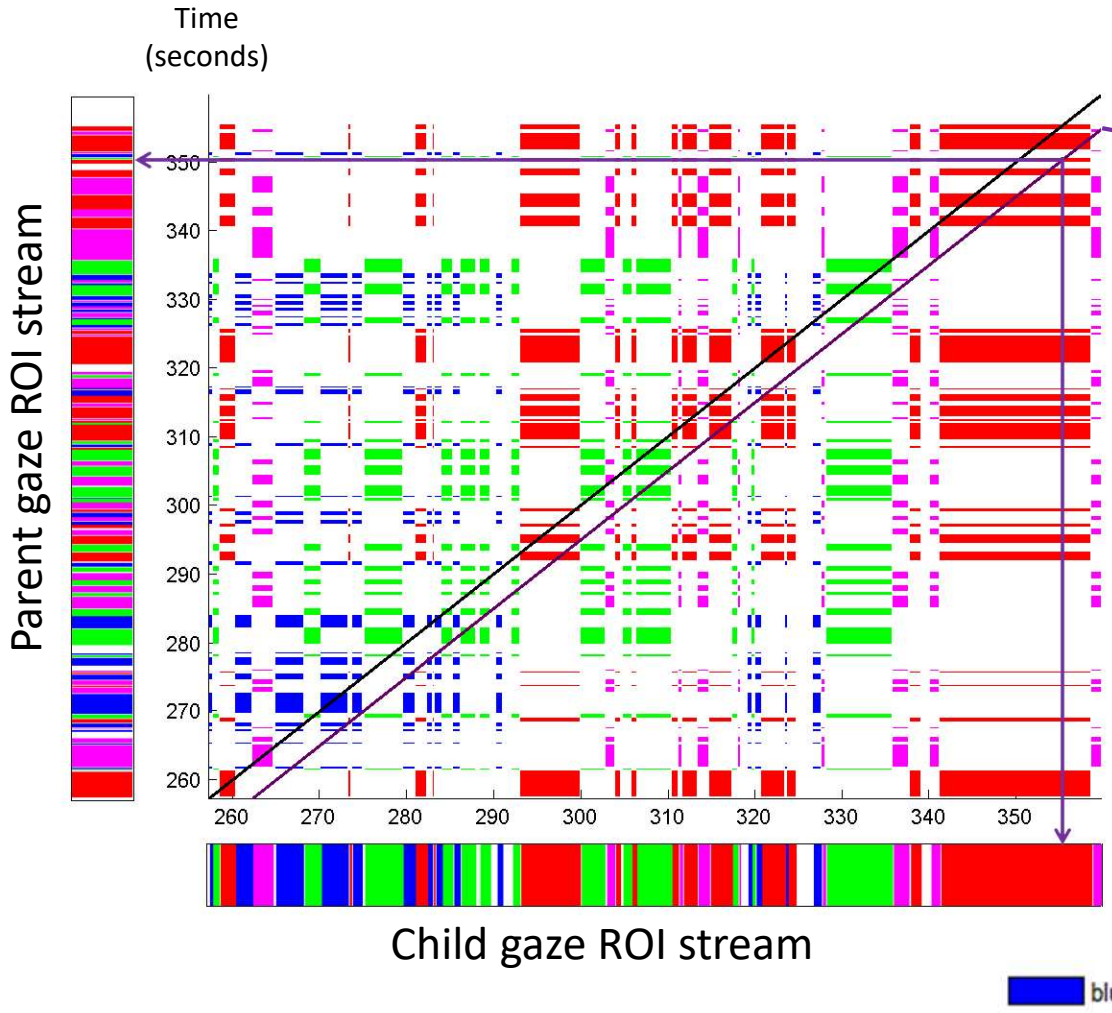
Non-Diagonal Line:
time-shifted match

$categorical\ value_x(j)$
vs
$categorical\ value_y(i)$

$j = i + 5s$

blue object | green object | red object | face

the parent's ROI at 350s
= the child's ROI at 355s



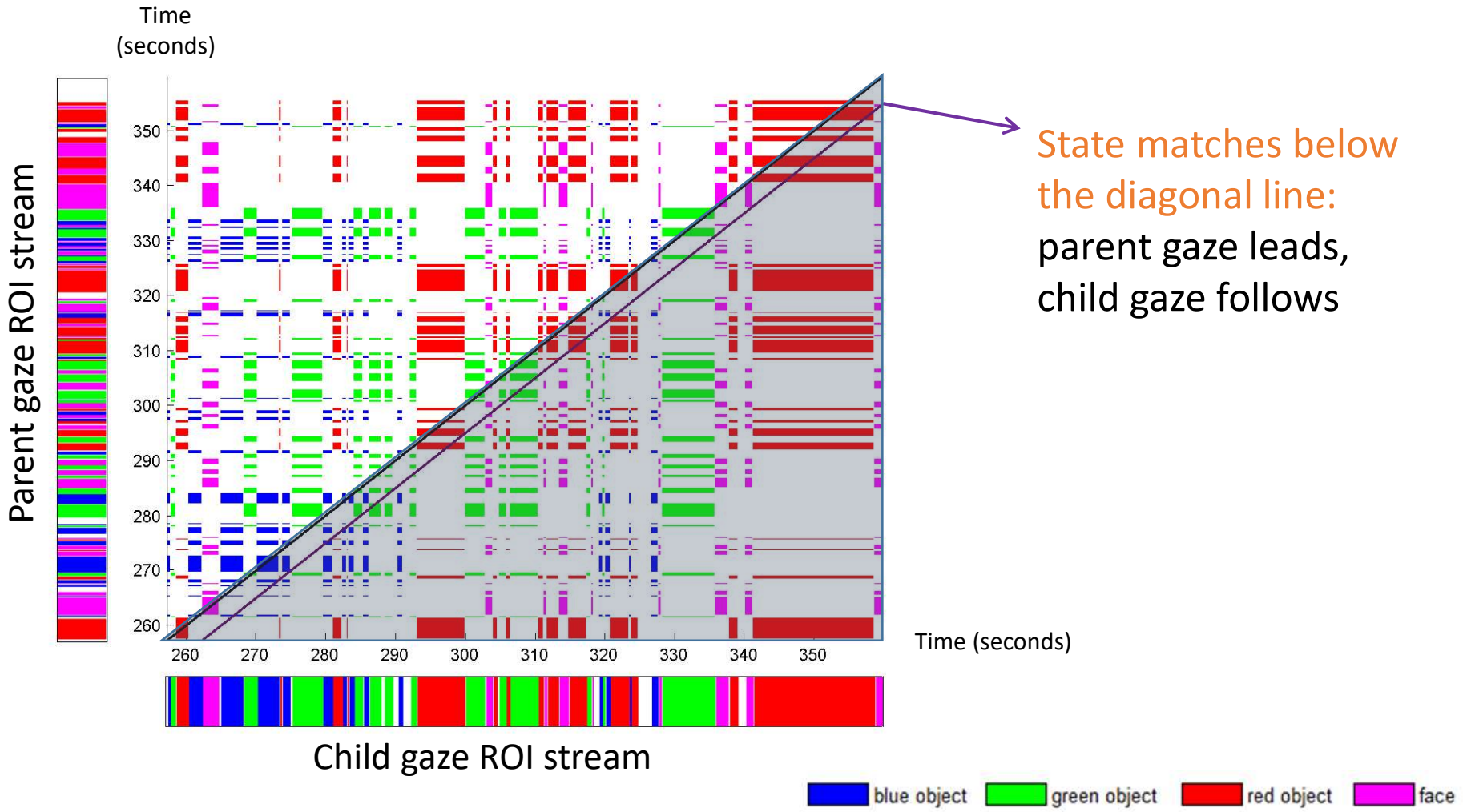
Non-Diagonal Line:
time-shifted match

$categorical\ value_x(j)$
vs
$categorical\ value_y(i)$

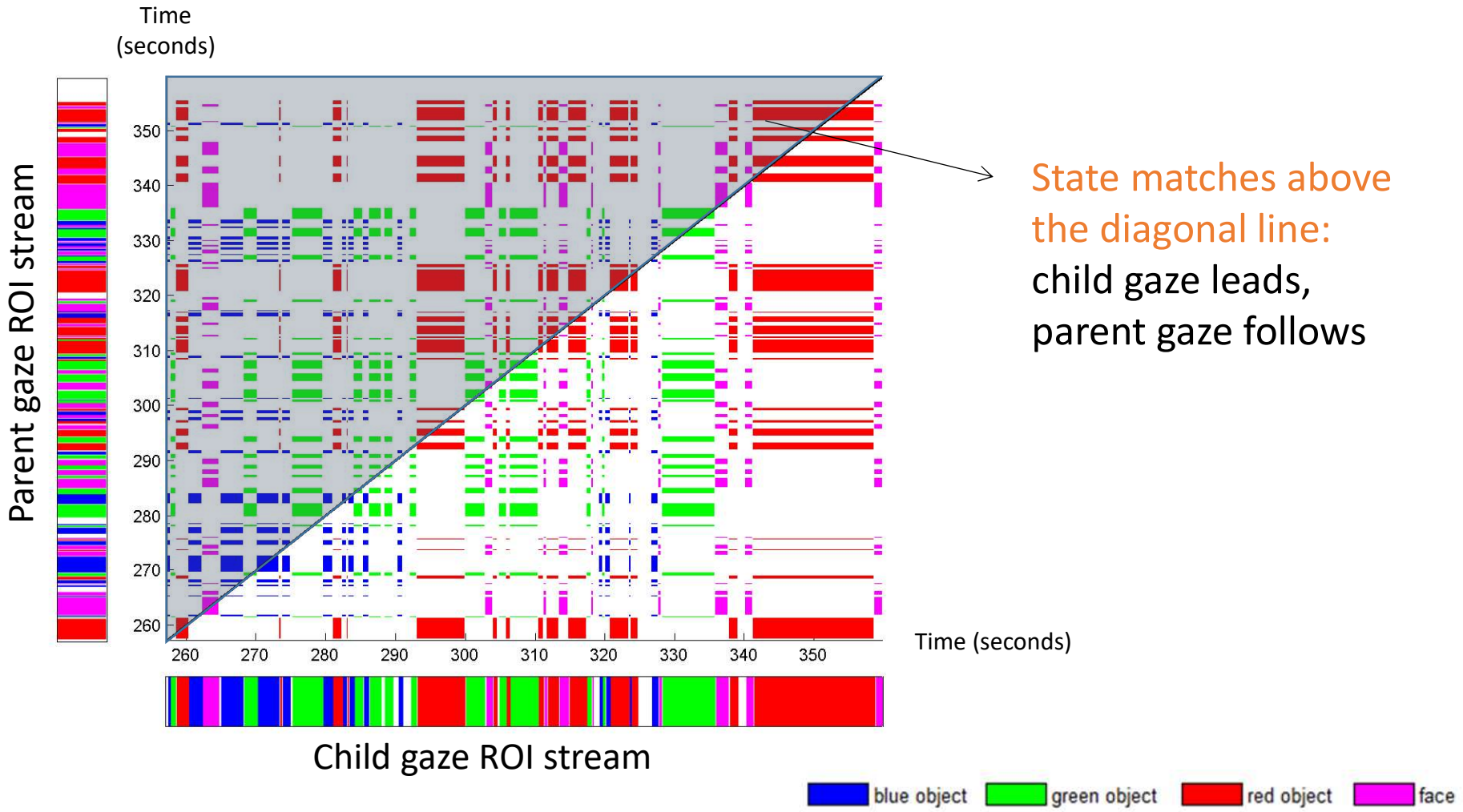
$j = i + 5s$

blue object green object red object face

time of the parent‘s action < time of the child’s action

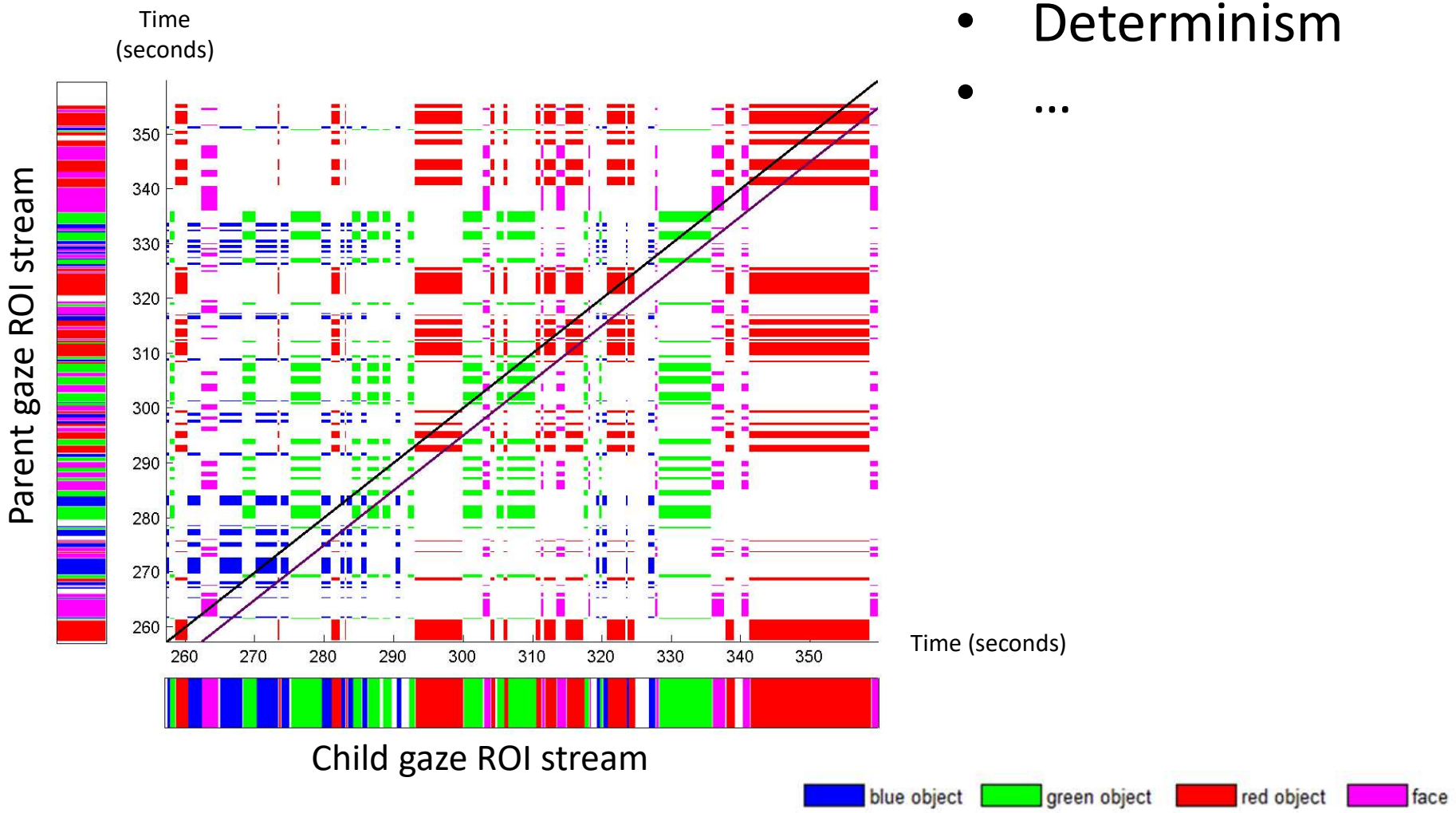


time of the parent‘s action > time of the child’s action

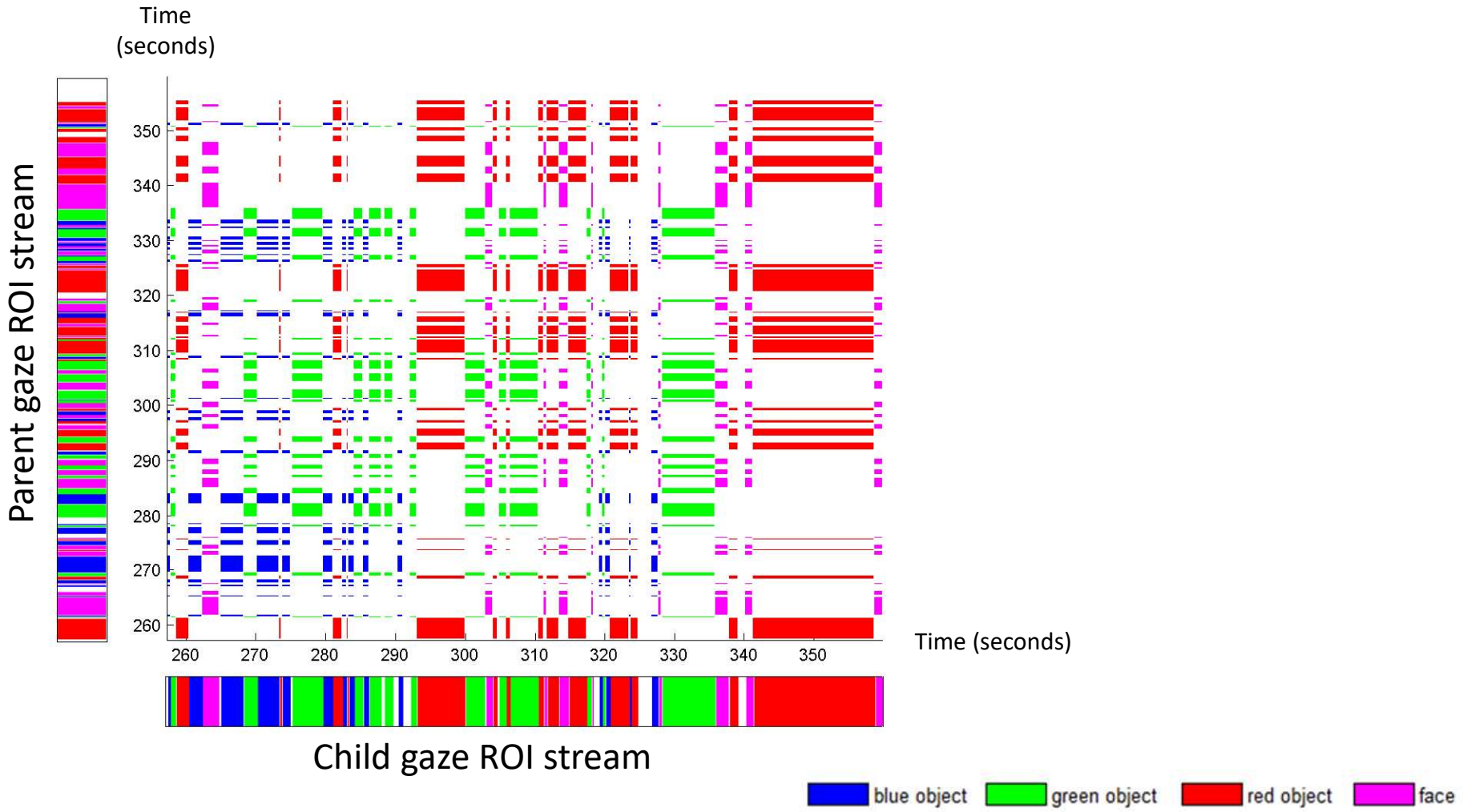


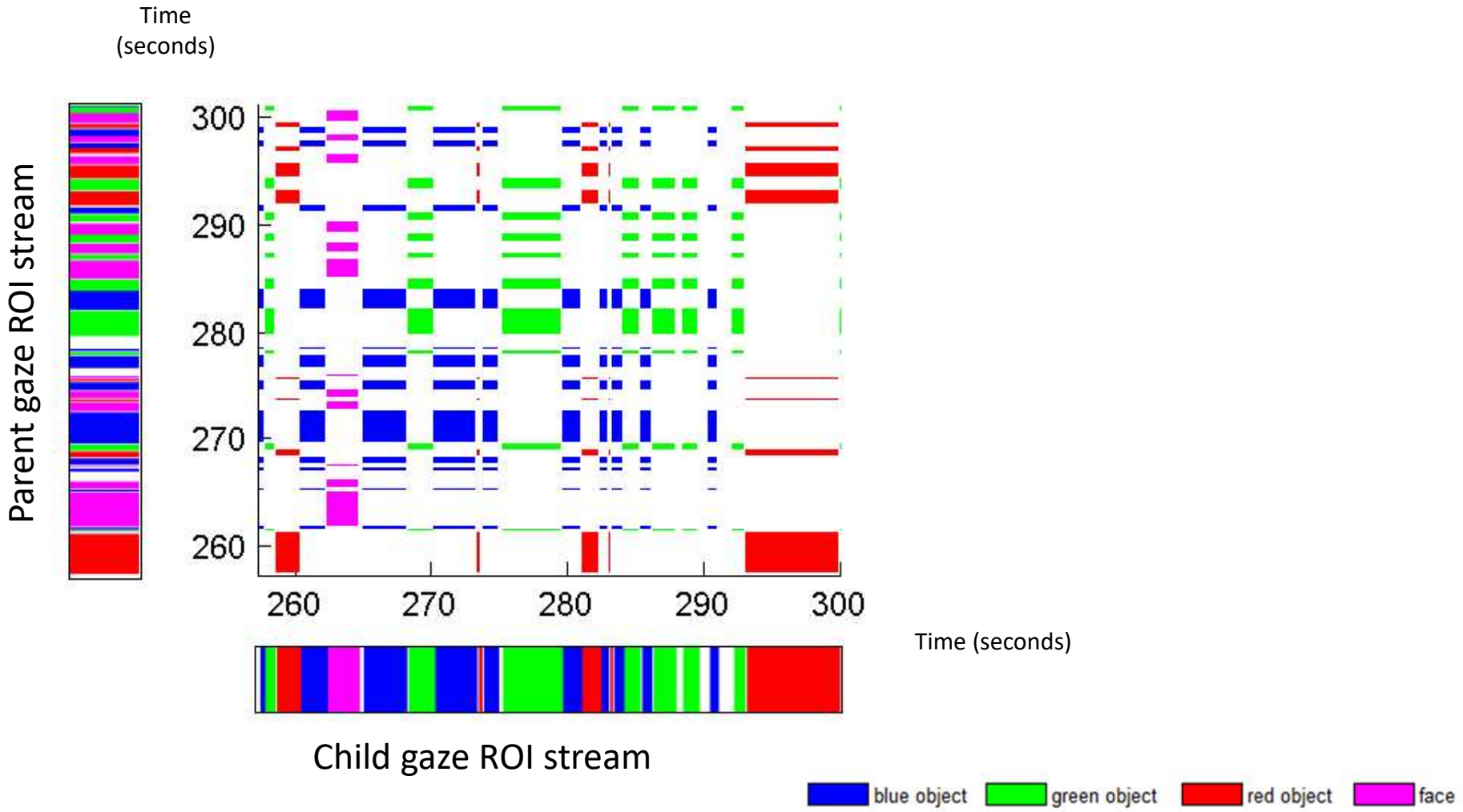
Cross Recurrence Quantification Analysis is mostly calculated based on point and line structures.

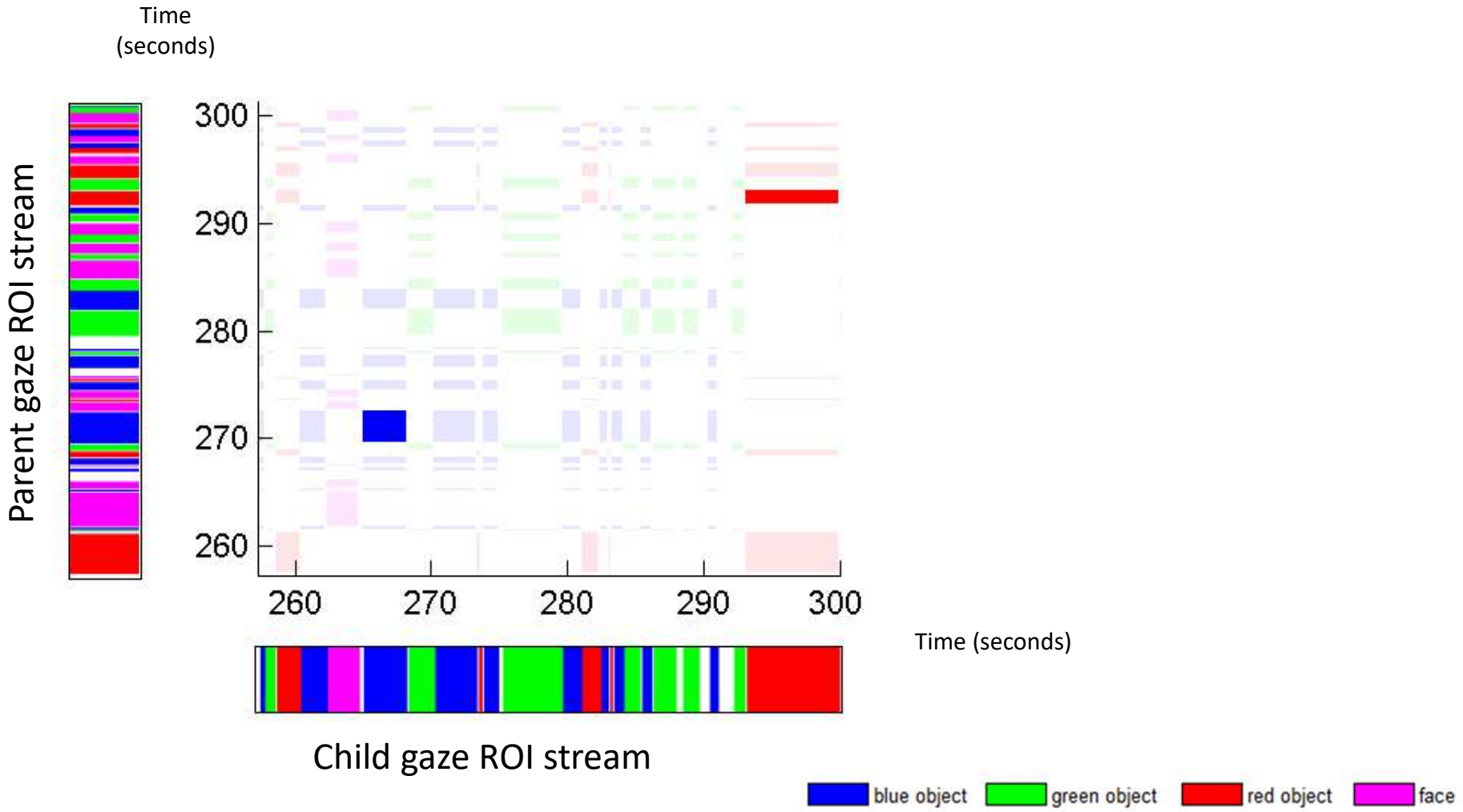
- Recurrence Rate
- Determinism
- …



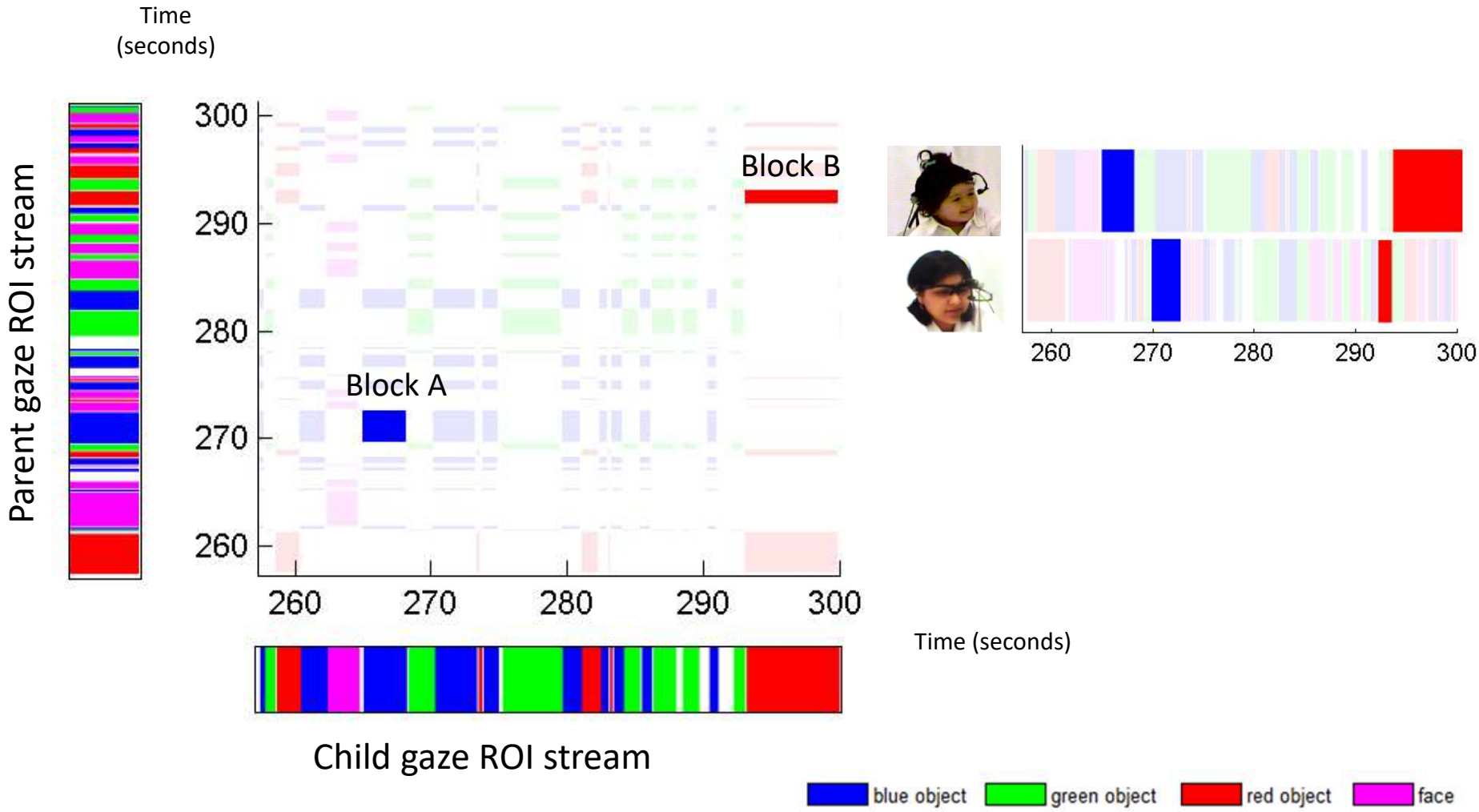
Adjacent points with the same categorical value (cv) can be grouped into one block.




Time
(seconds)
Parent gaze ROI stream
300
290
280
270
260
260
270
280
290
300
Time (seconds)
Child gaze ROI stream
blue object
green object
red object
face


Time
(seconds)
Parent gaze ROI stream
300
290
280
270
260
260
270
280
290
300
Time (seconds)
Child gaze ROI stream
blue object
green object
red object
face

And such block representation intuitively maps back to the sequence of events in the original data streams.



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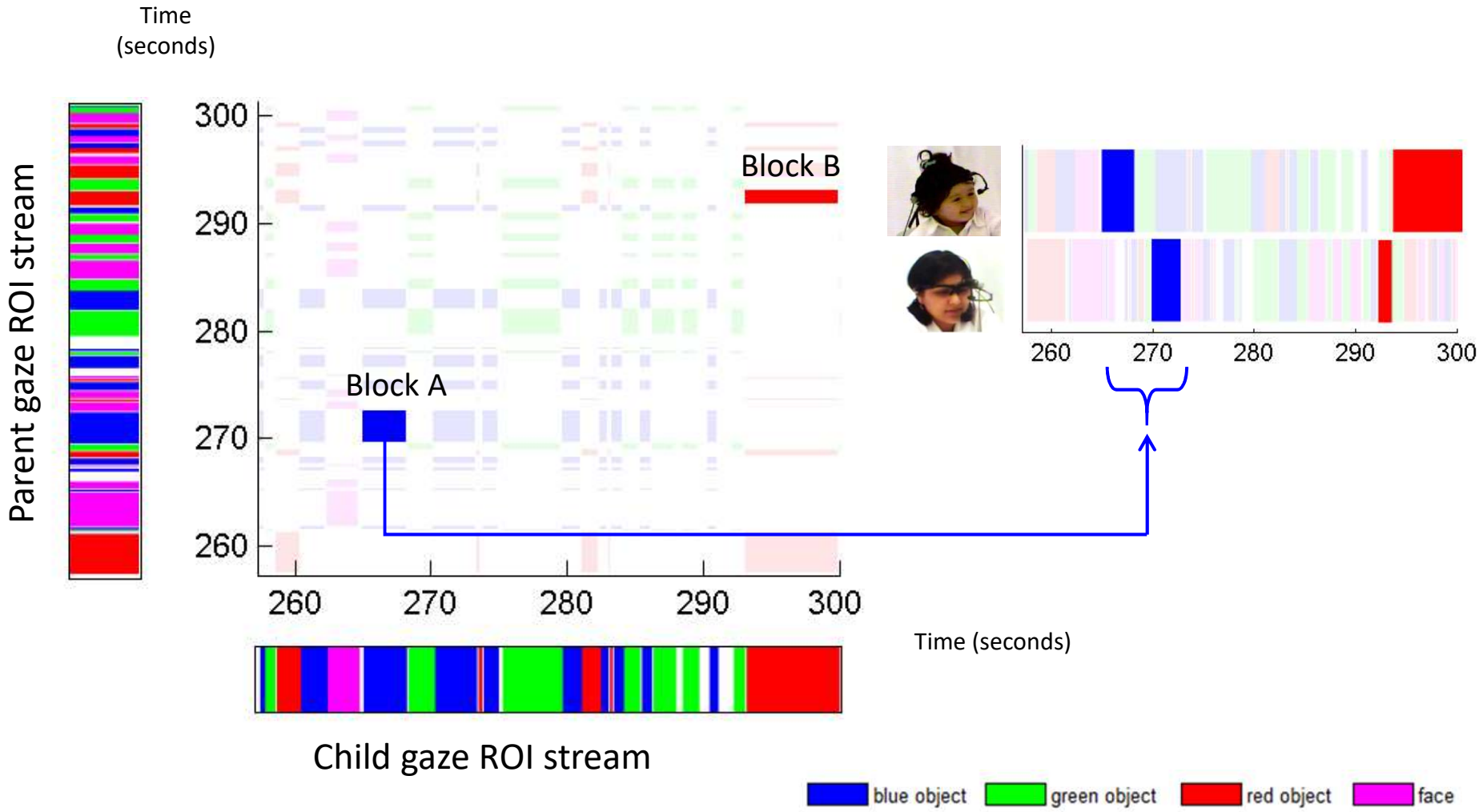

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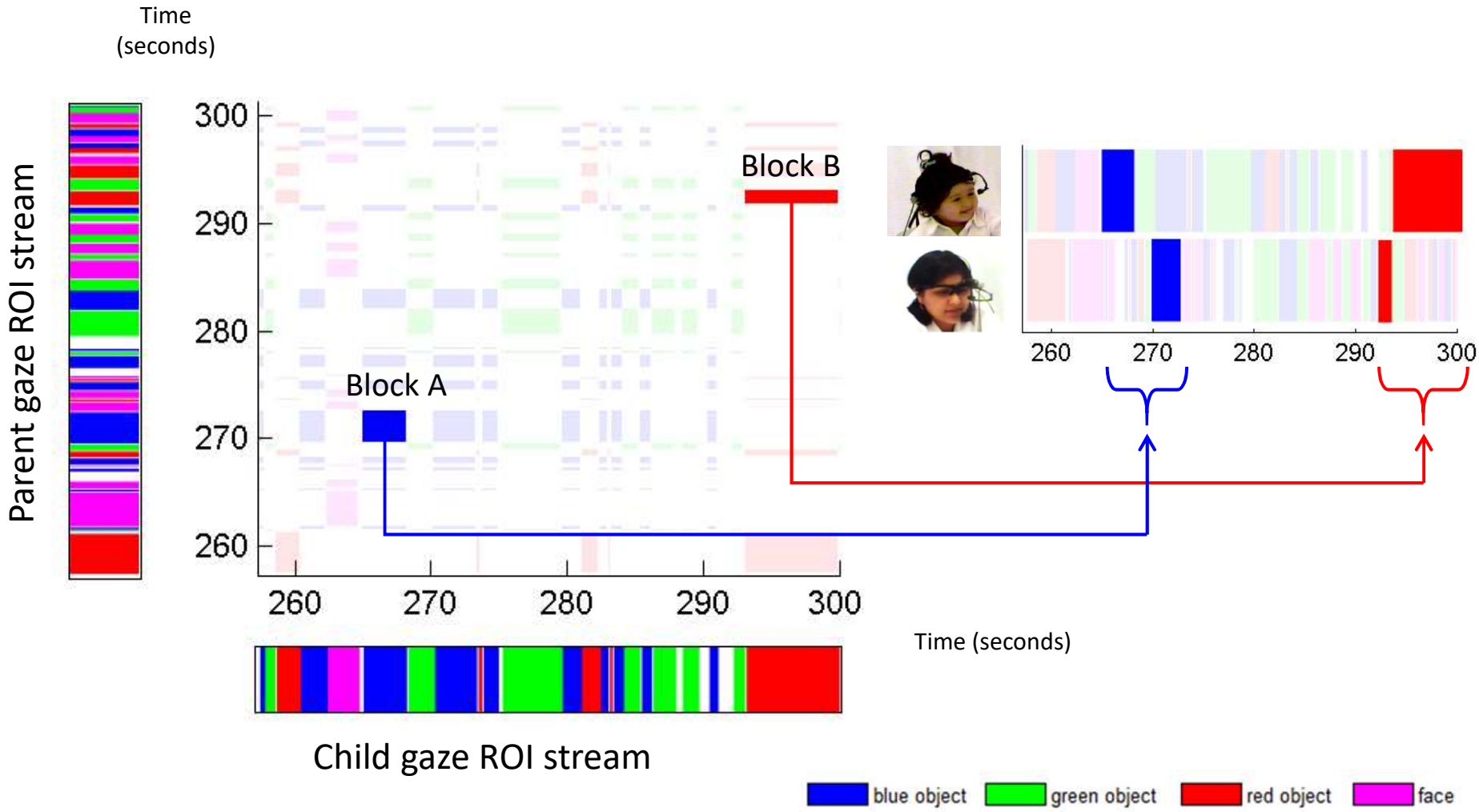
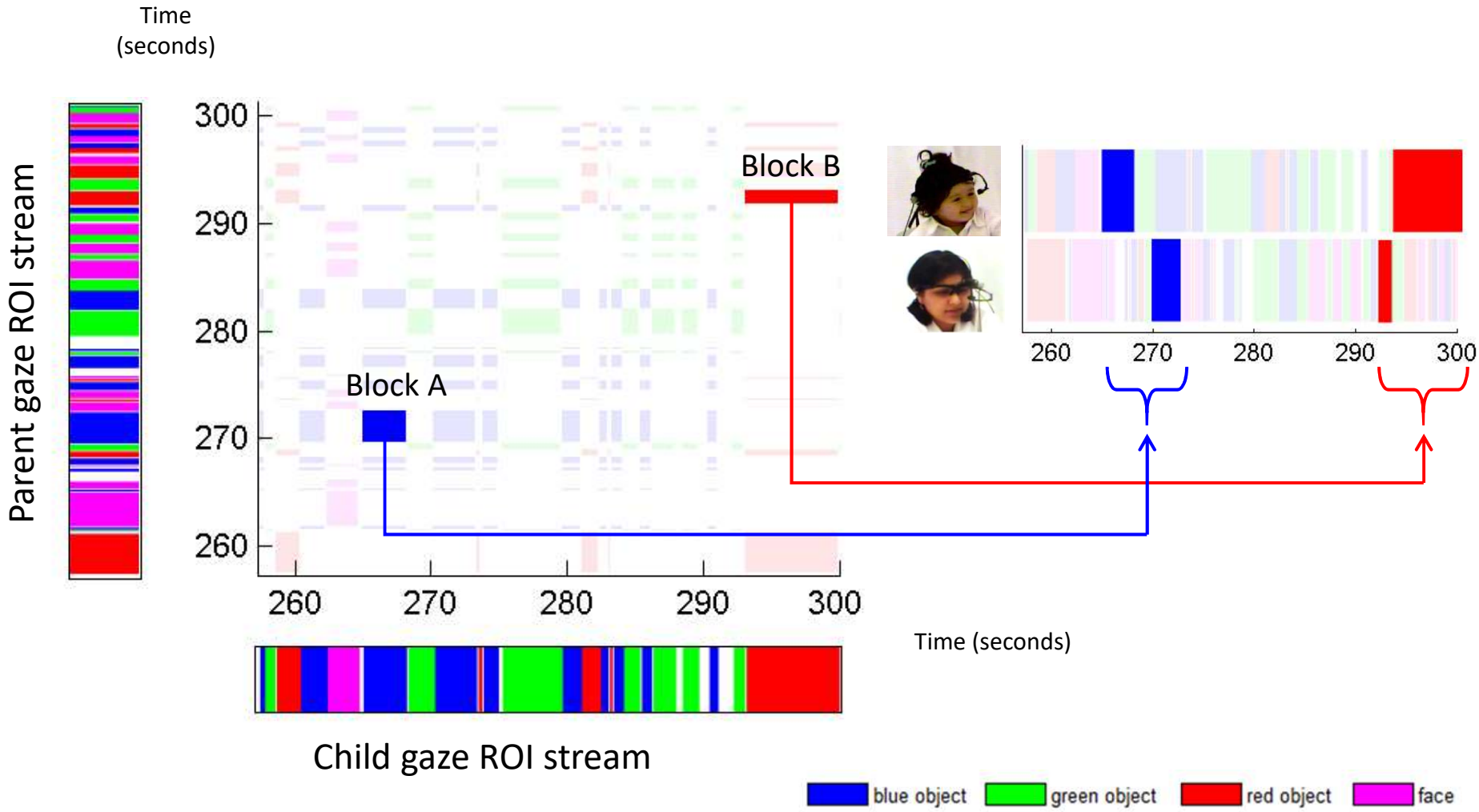


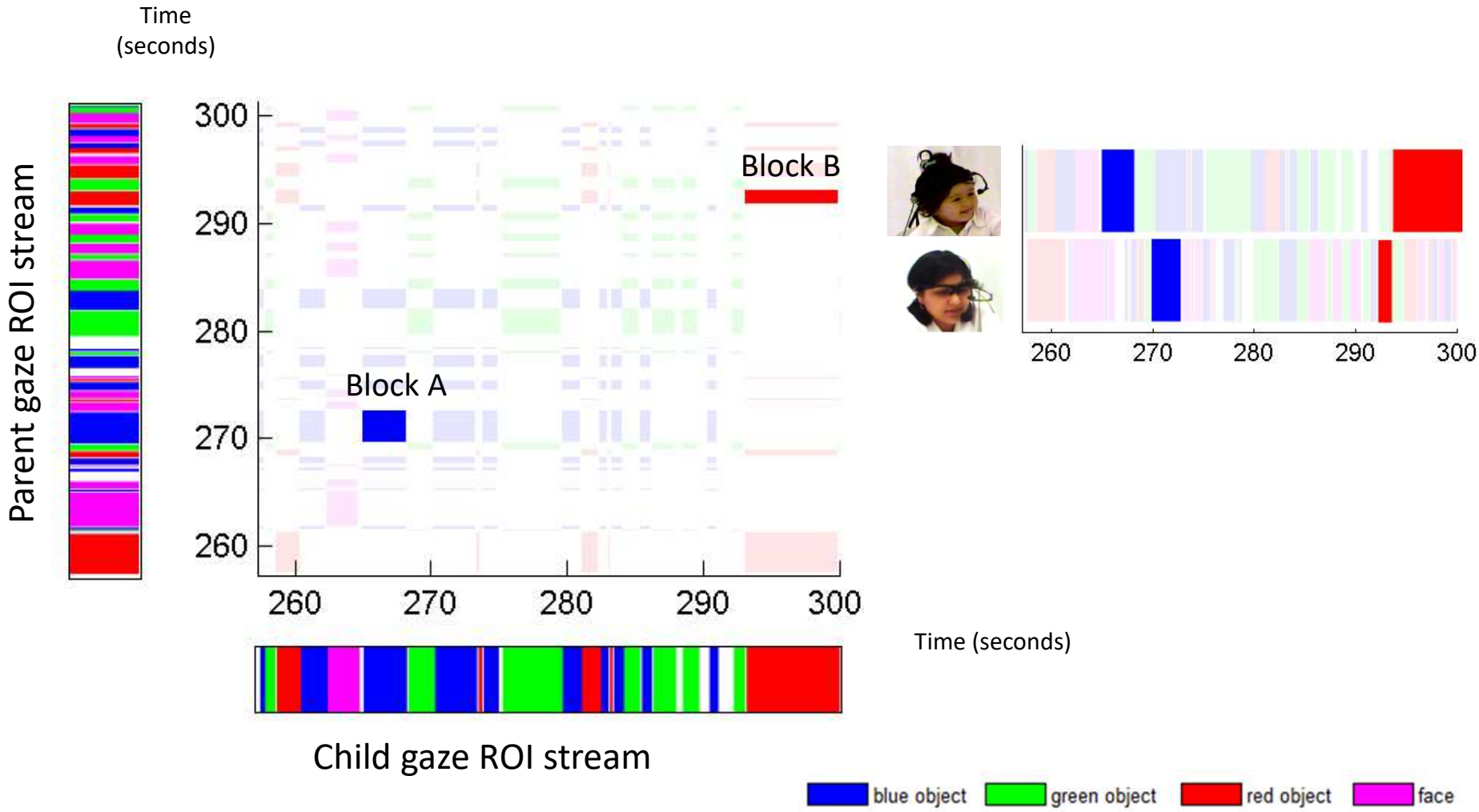
We define such block representation as

Cross Recurrence Block (CRB)



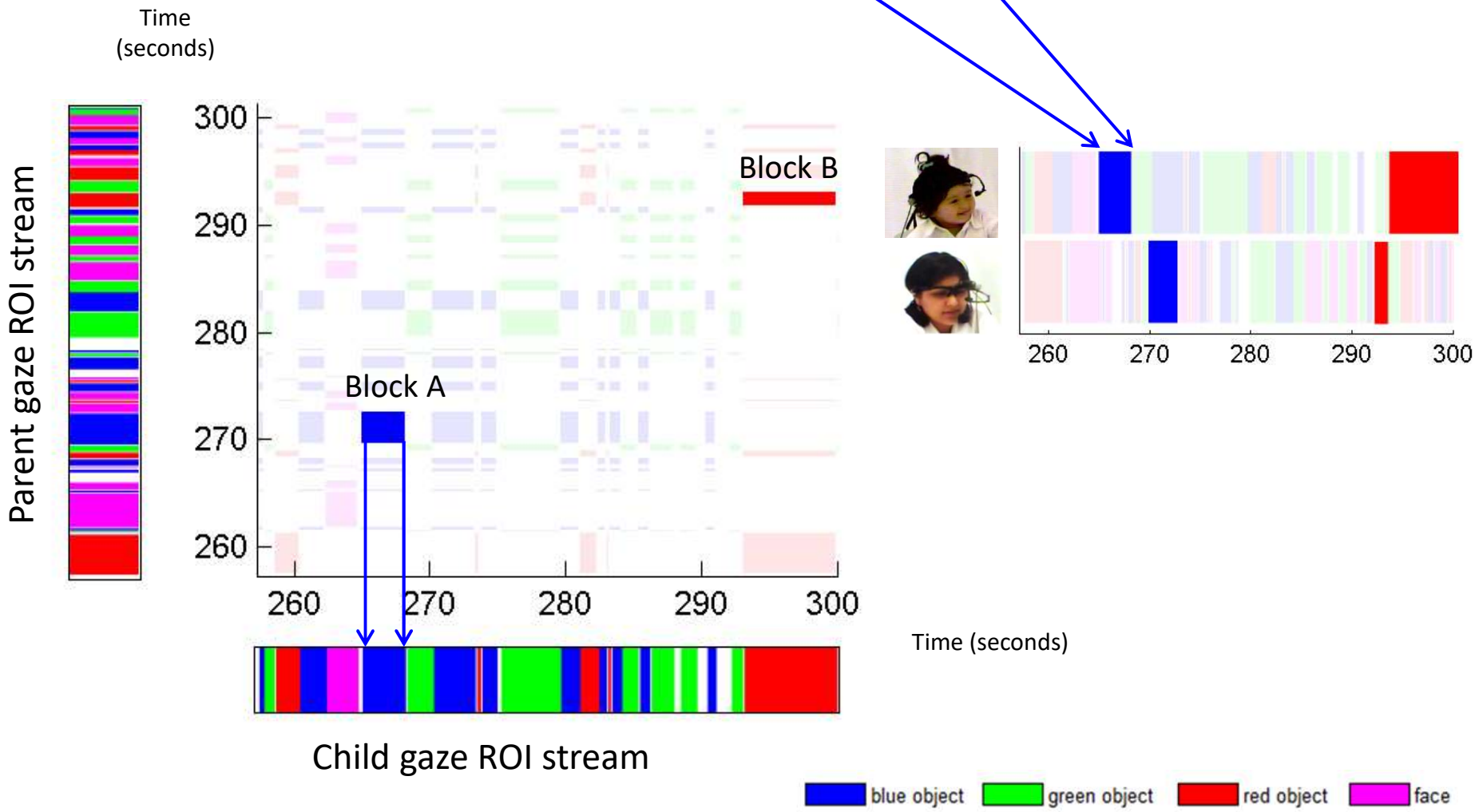
Cross Recurrence Block

$$CRB: < x_{start}, x_{end}, y_{start}, y_{end}, cv >$$



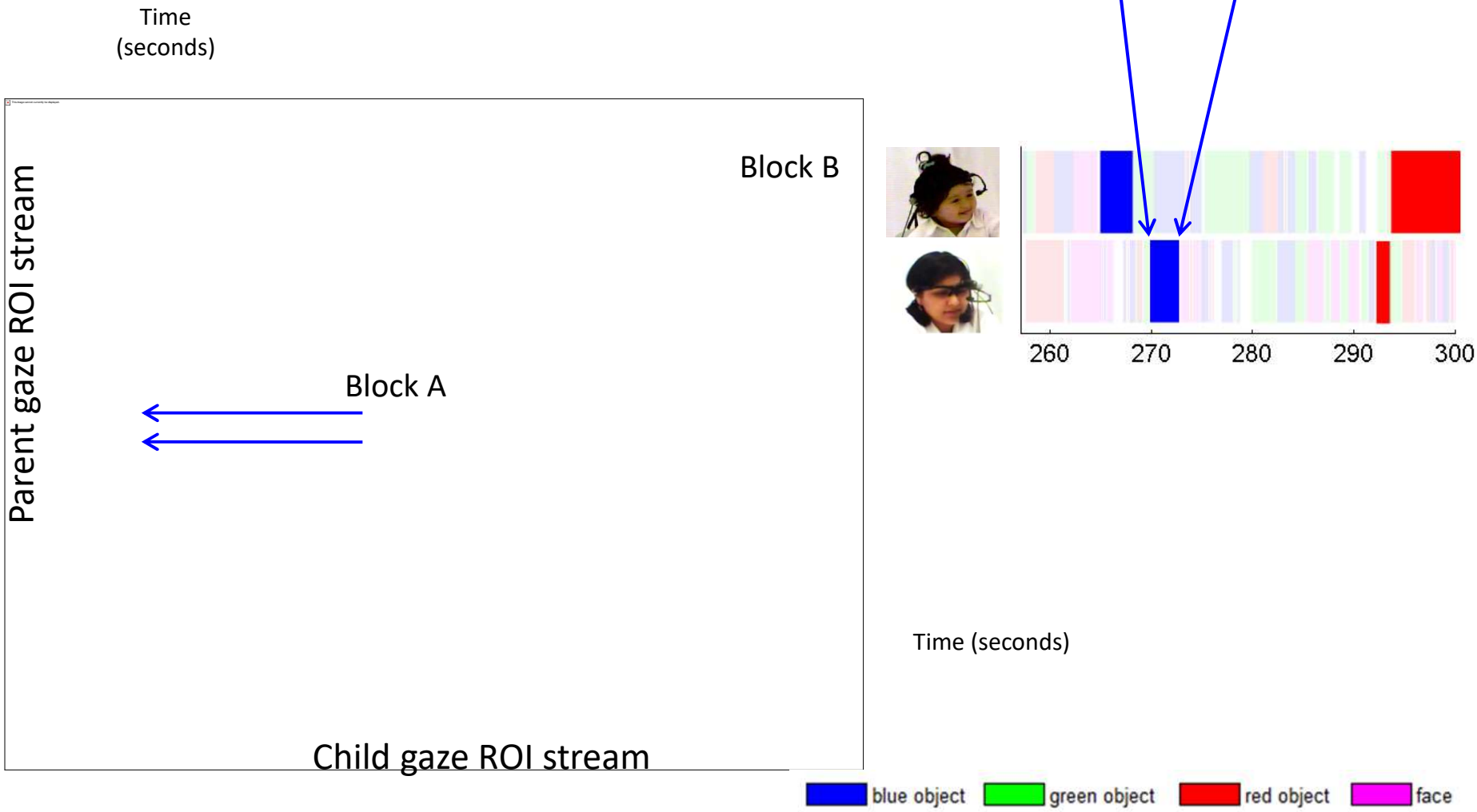
Cross Recurrence Block

$$CRB: < x_{start}, x_{end}, y_{start}, y_{end}, cv >$$



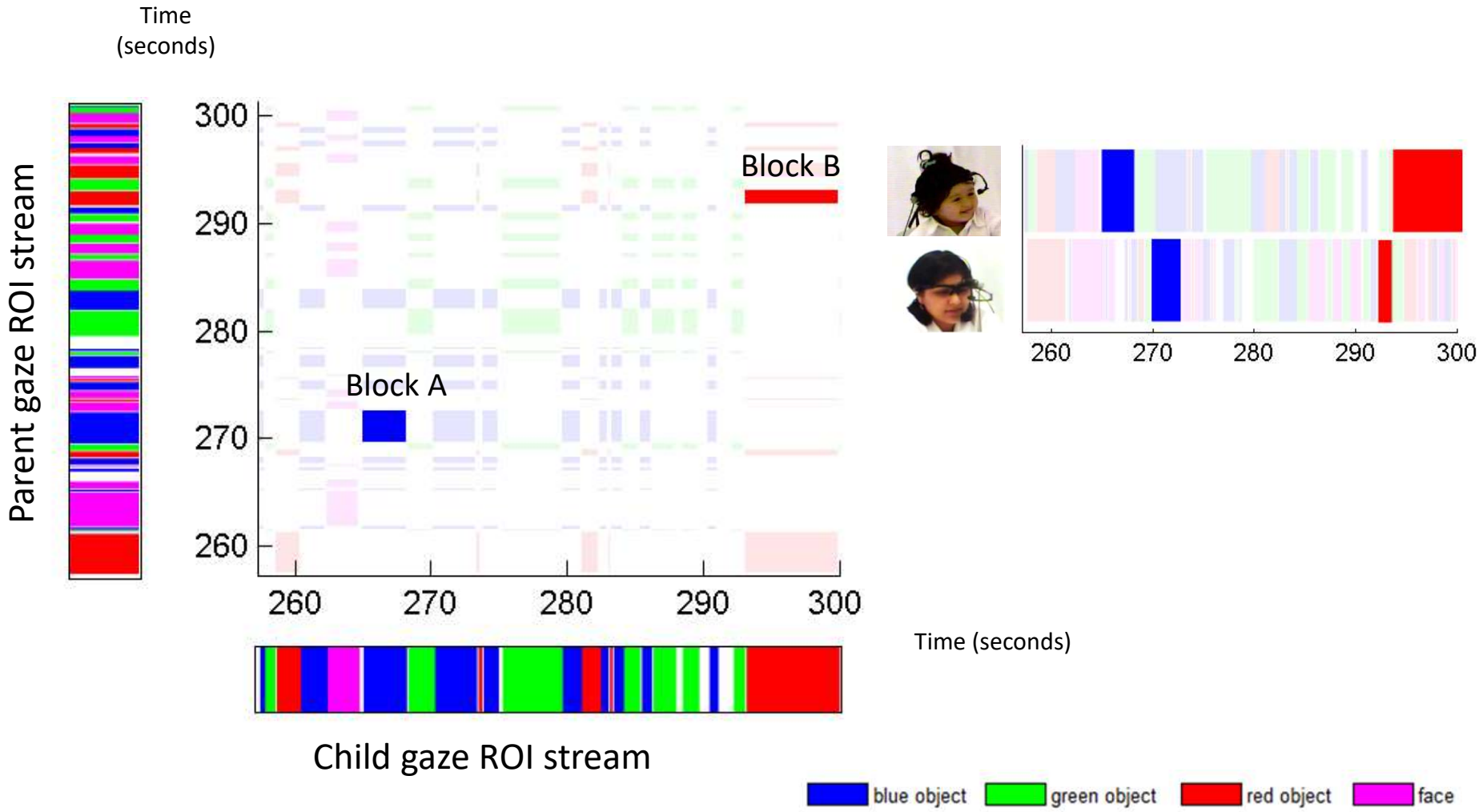
Cross Recurrence Block

$$CRB: < x_{start}, x_{end}, y_{start}, y_{end}, cv >$$



Cross Recurrence Block

$$CRB: < x_{start}, x_{end}, y_{start}, y_{end}, cv >$$

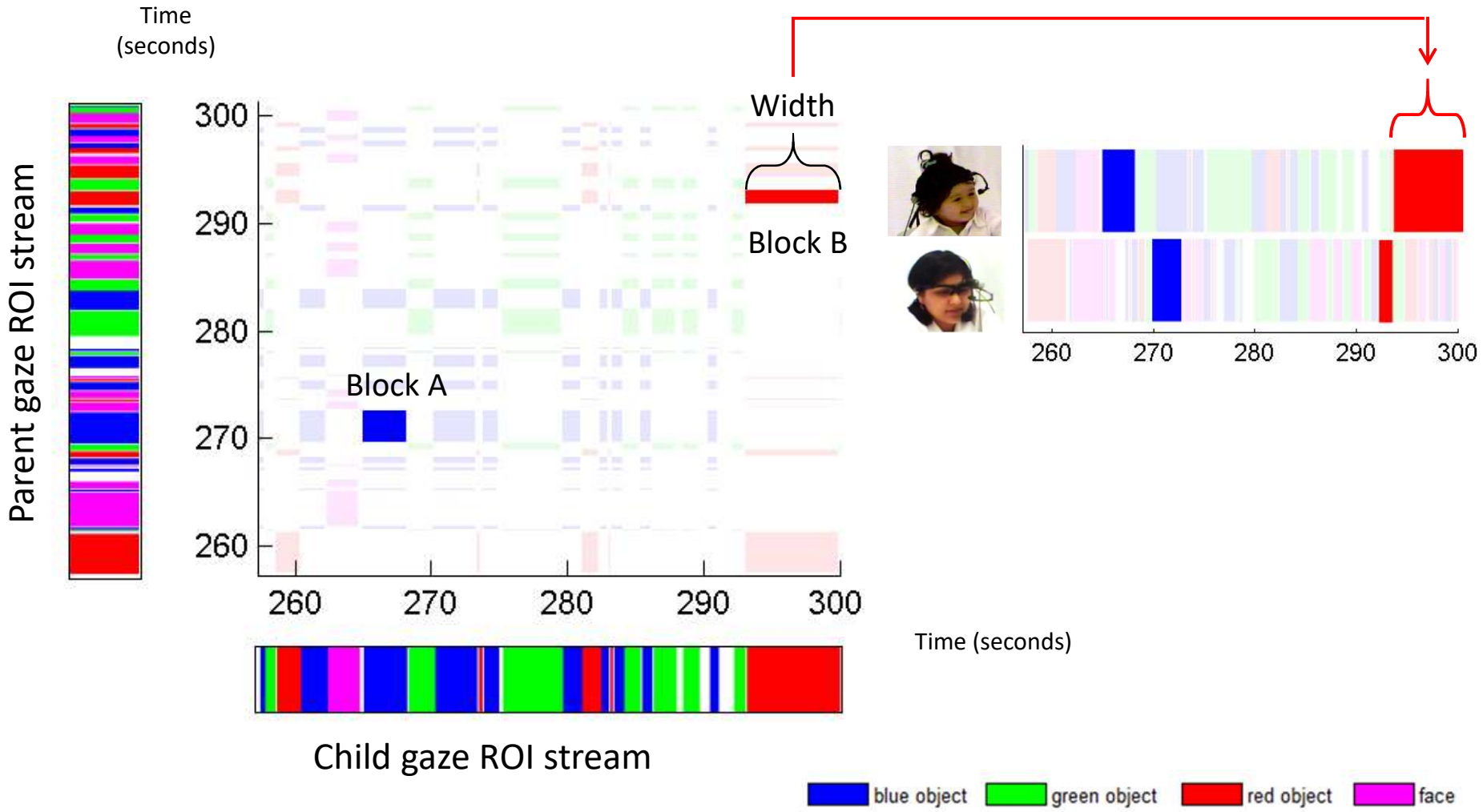


Cross Recurrence Block (CRB)

- A suite of quantitative measurements can be extracted based on CRB representation to describe coordinative structures in details
  - Width
  - Height
  - Shape
  - Time lag

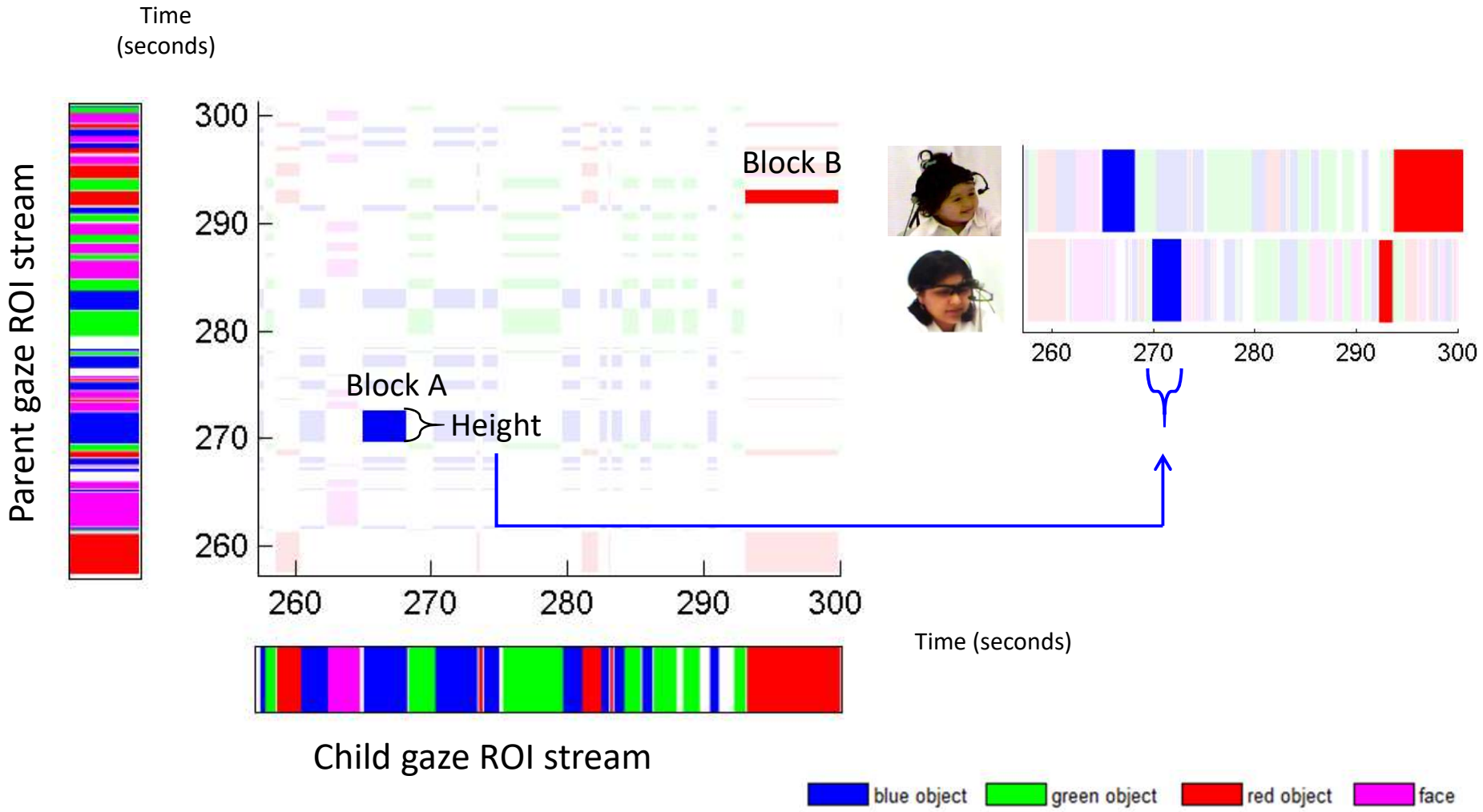
$$Width = x_{end} - x_{start}$$

Duration of $agent_x$'s participation

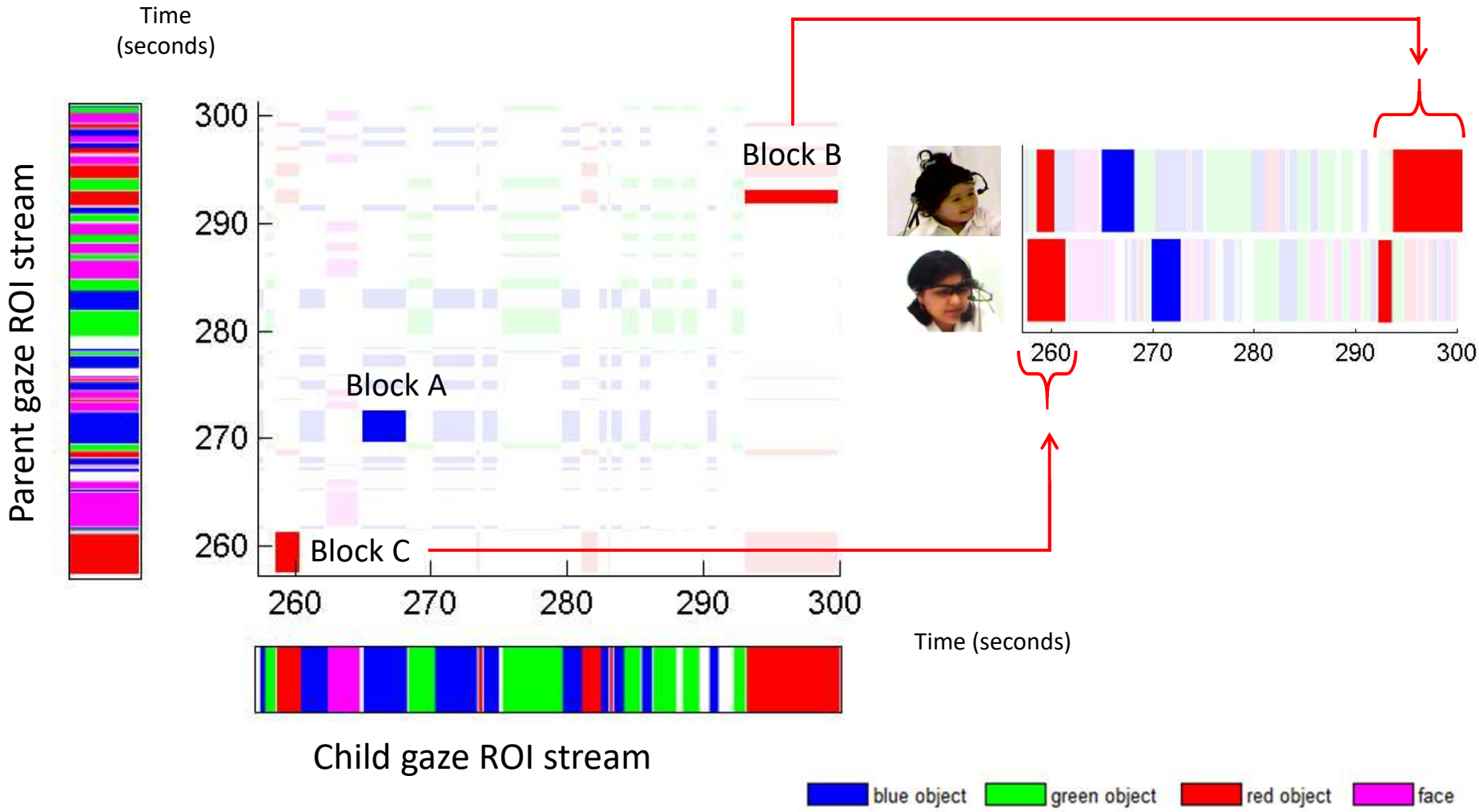


$$Height = y_{end} - y_{start}$$

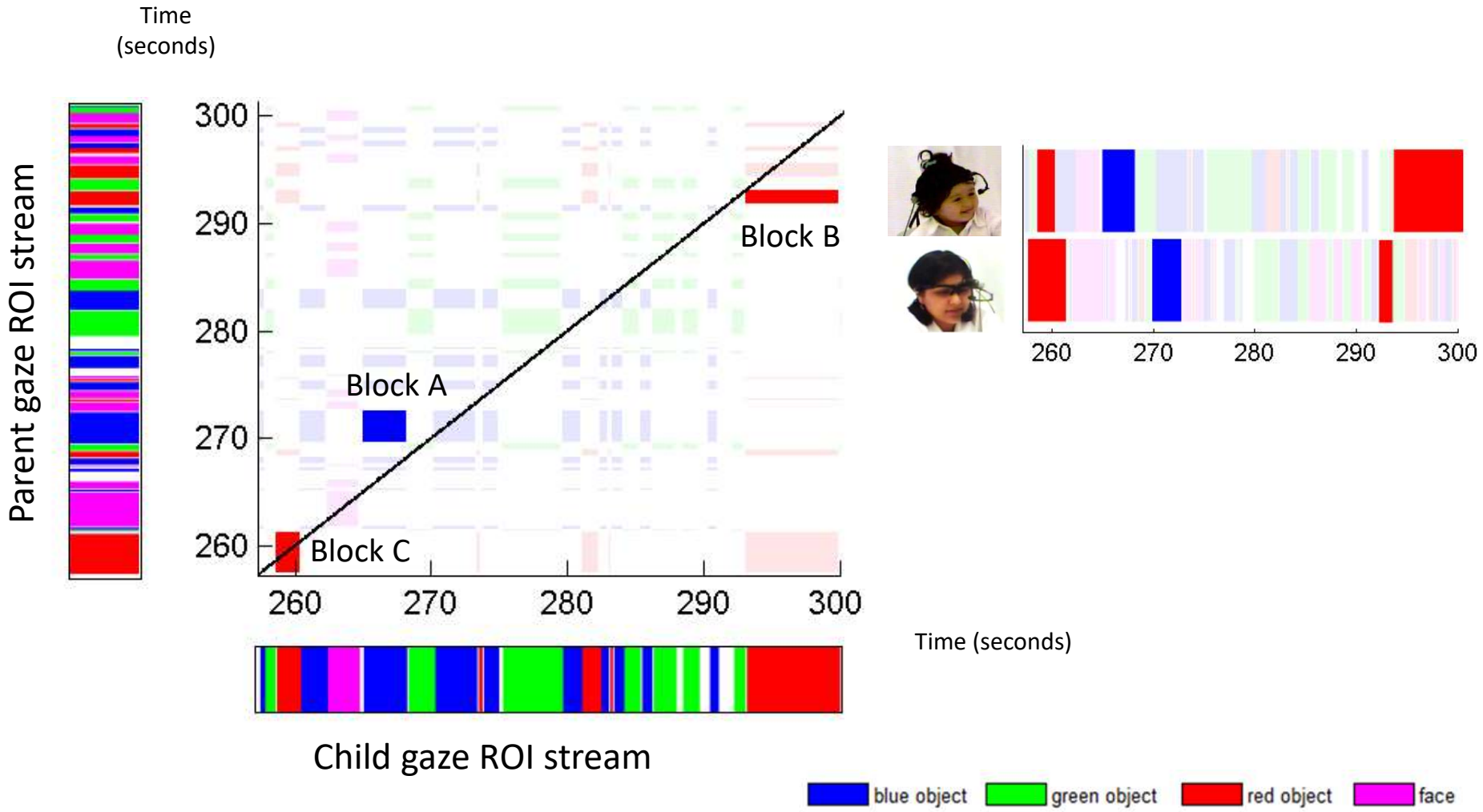
Duration of $agent_y$'s participation



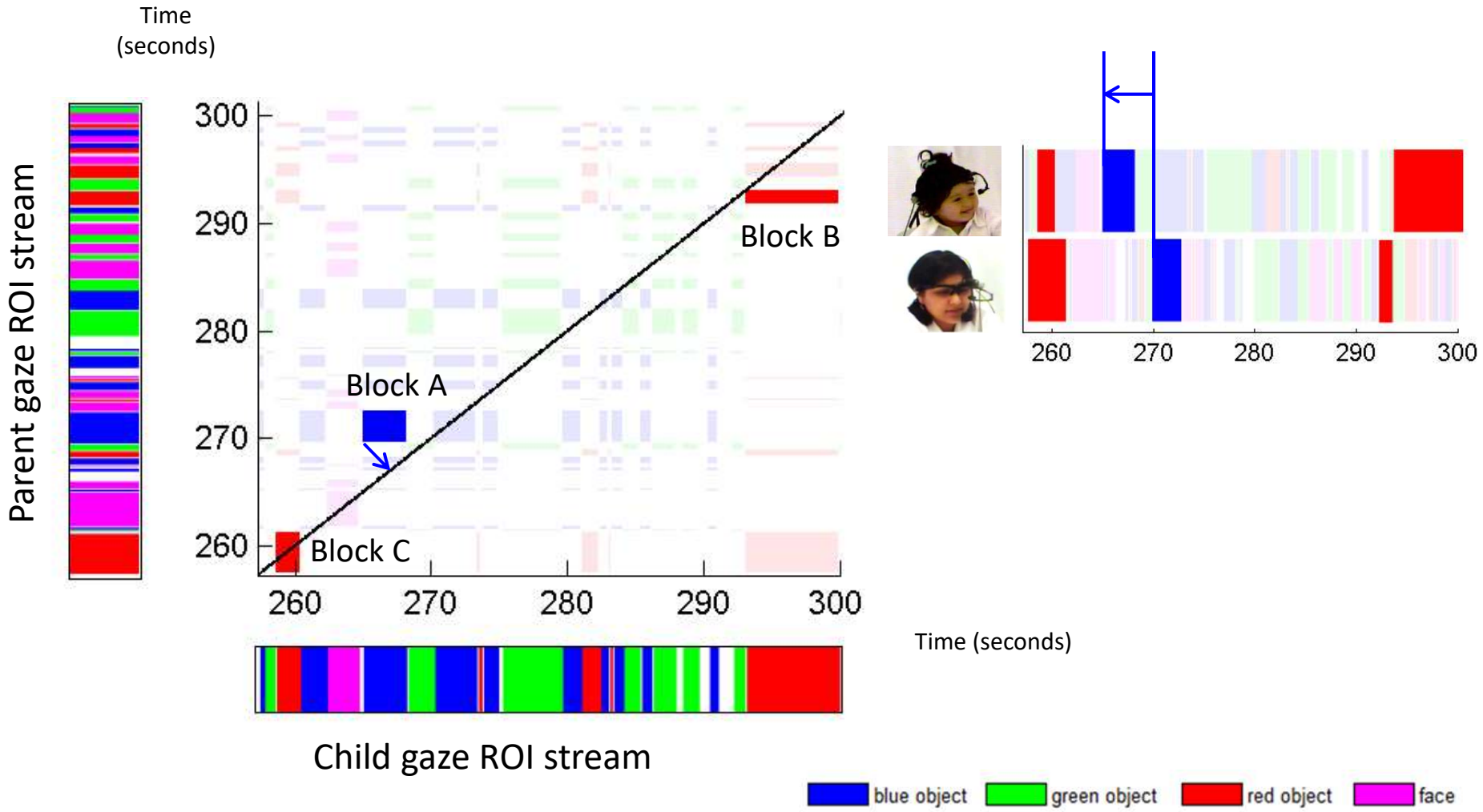
Shape: *horizontal vs vertical CRB*



Time lag: leading and following dynamics

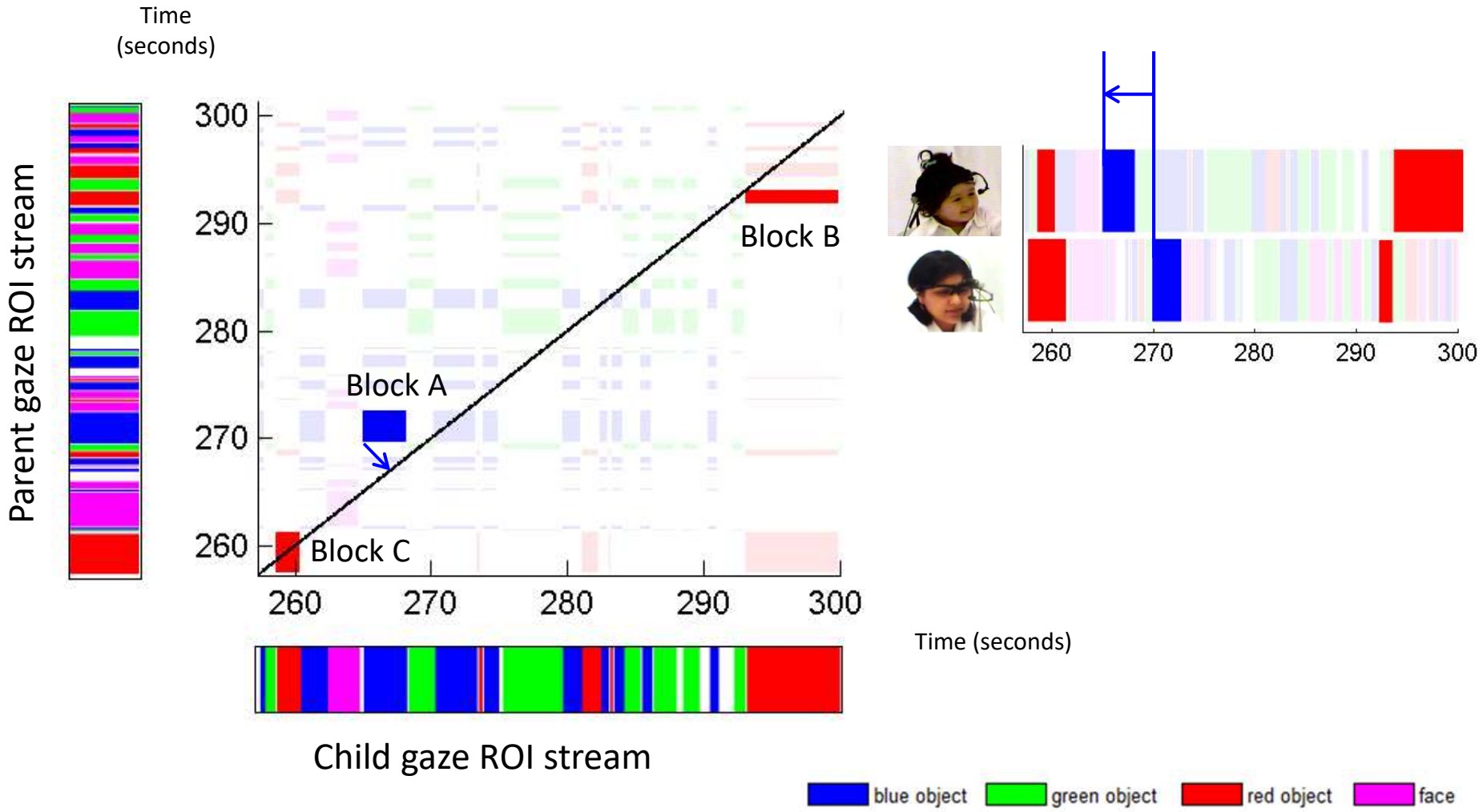


$$start\ time\ lag = y_{start} - x_{start}$$

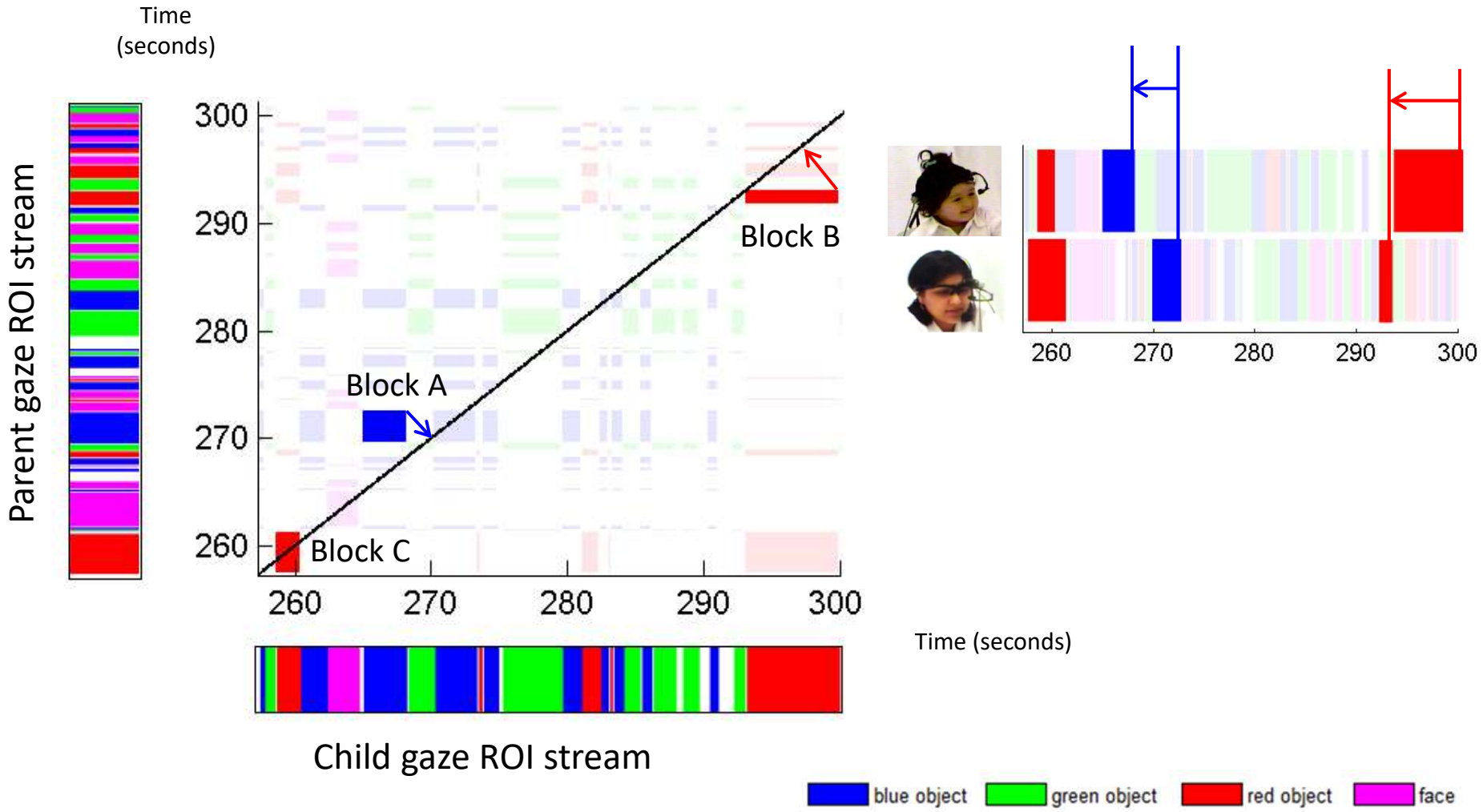


$$start\ time\ lag = y_{start} - x_{start}$$

start time lag > 0, child leads; lag < 0, parent leads

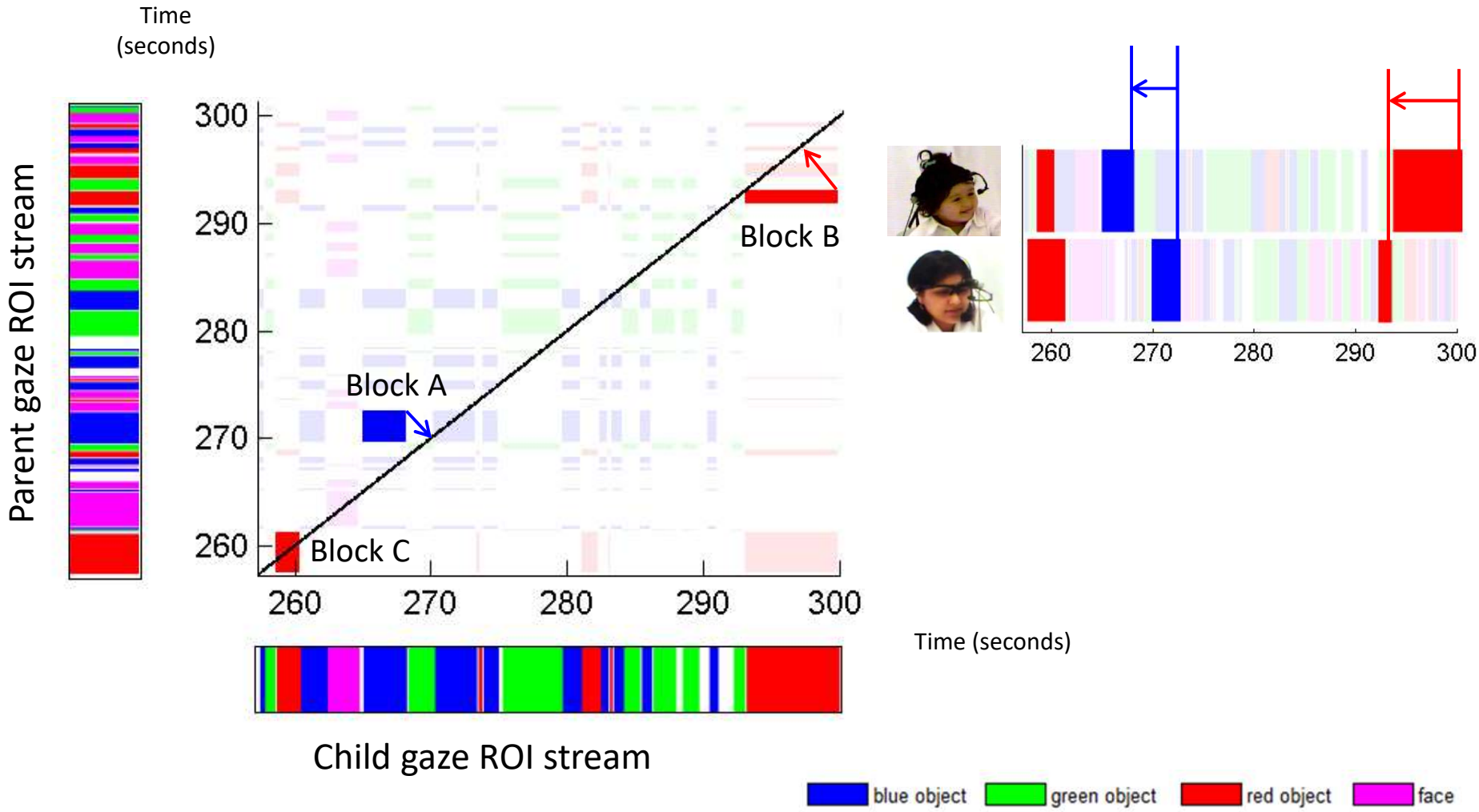


$$end\ time\ lag = y_{end} - x_{end}$$

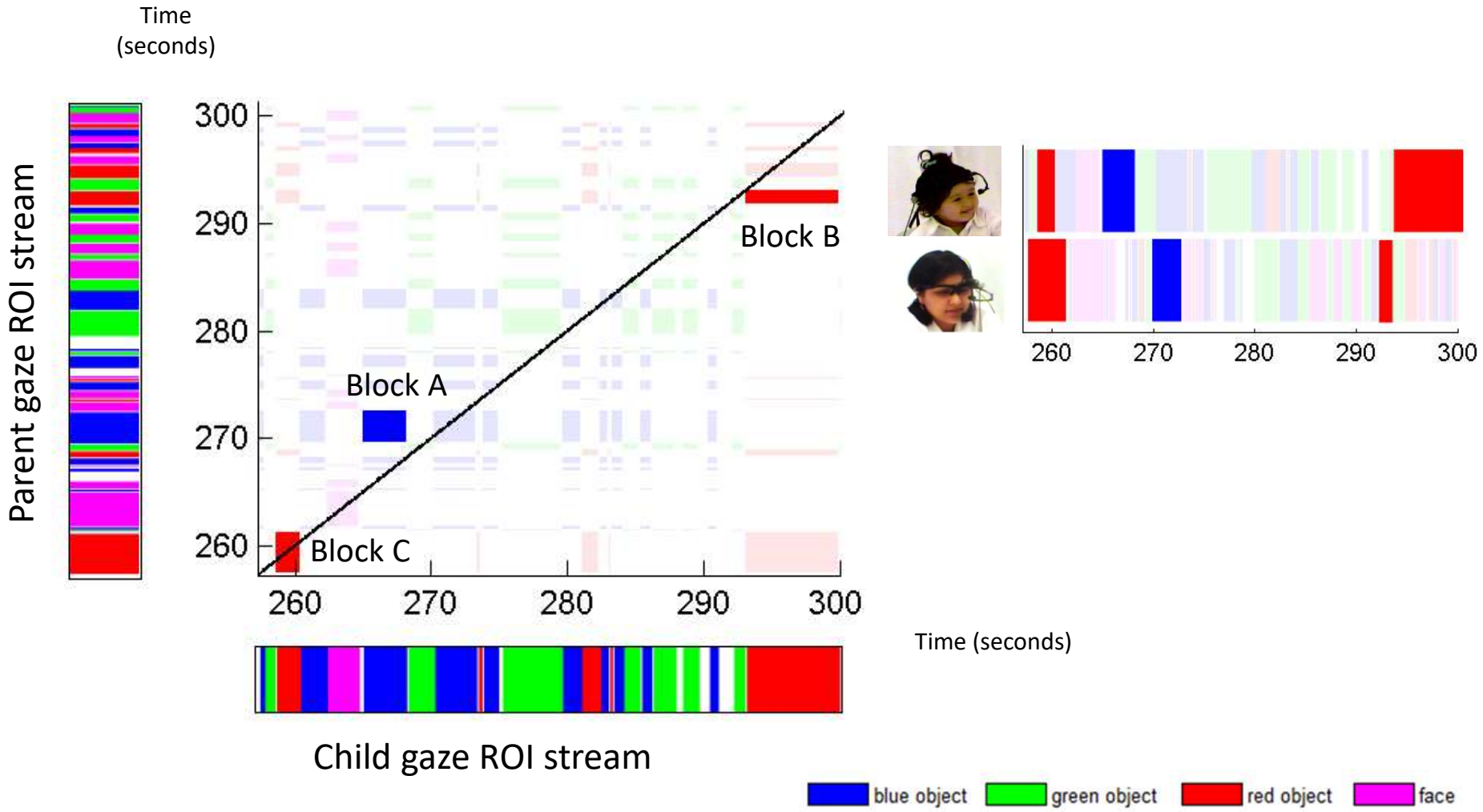


$$end\ time\ lag = y_{end} - x_{end}$$

end time lag > 0, child switches target ROI first

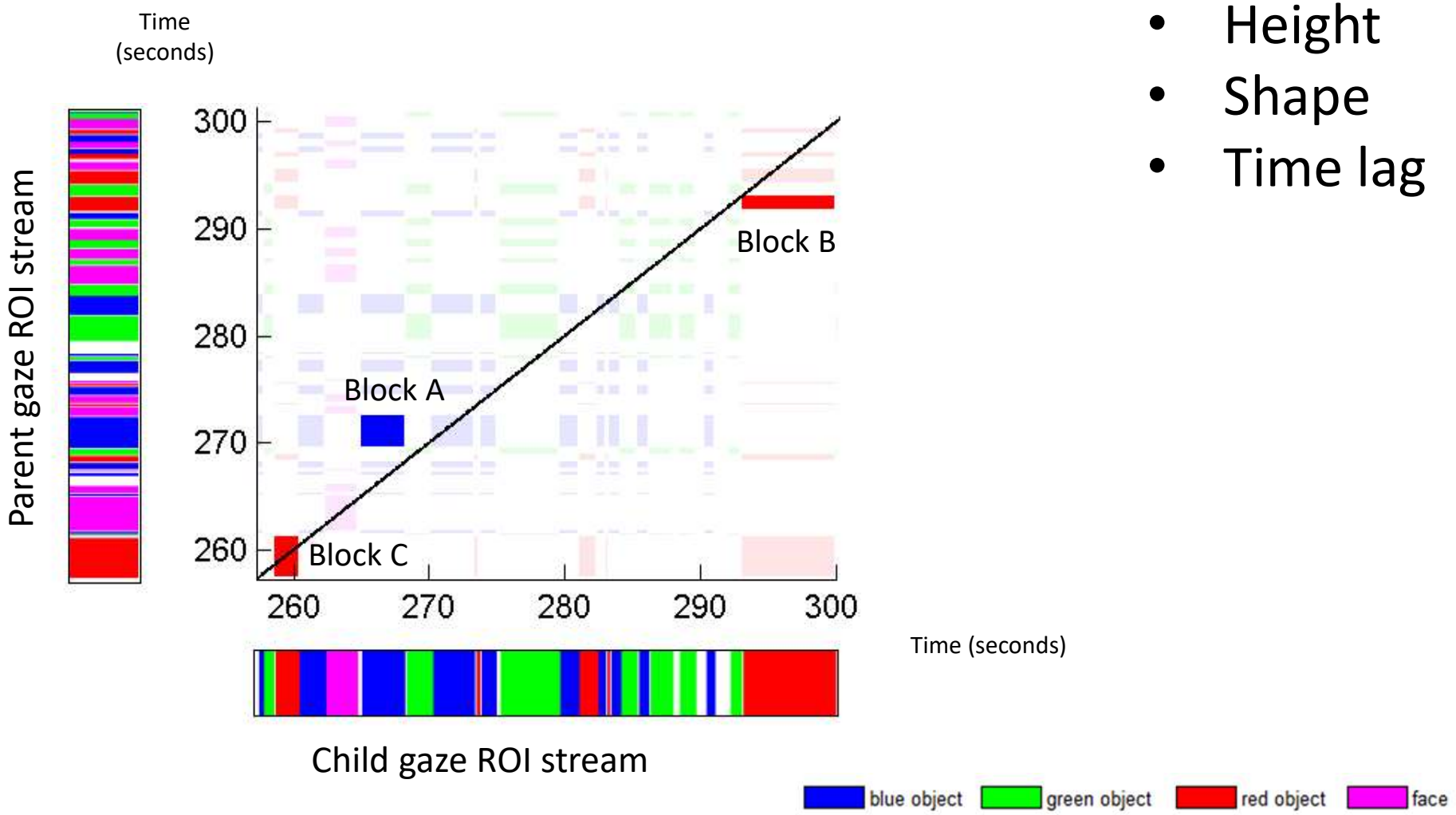


Time lag: who initiated; who switched first



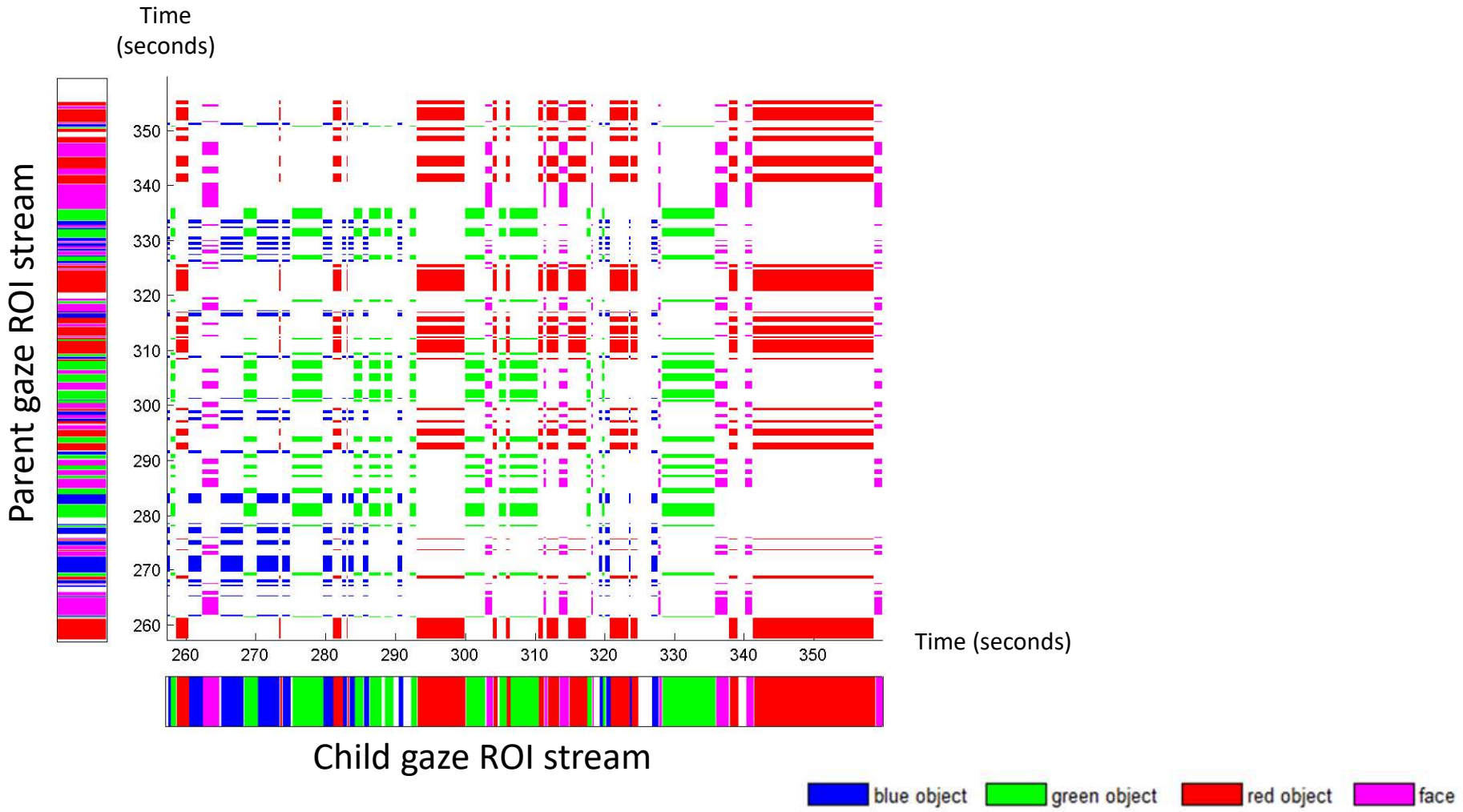
CRB based Quantitative Analysis

- Width
- Height
- Shape
- Time lag

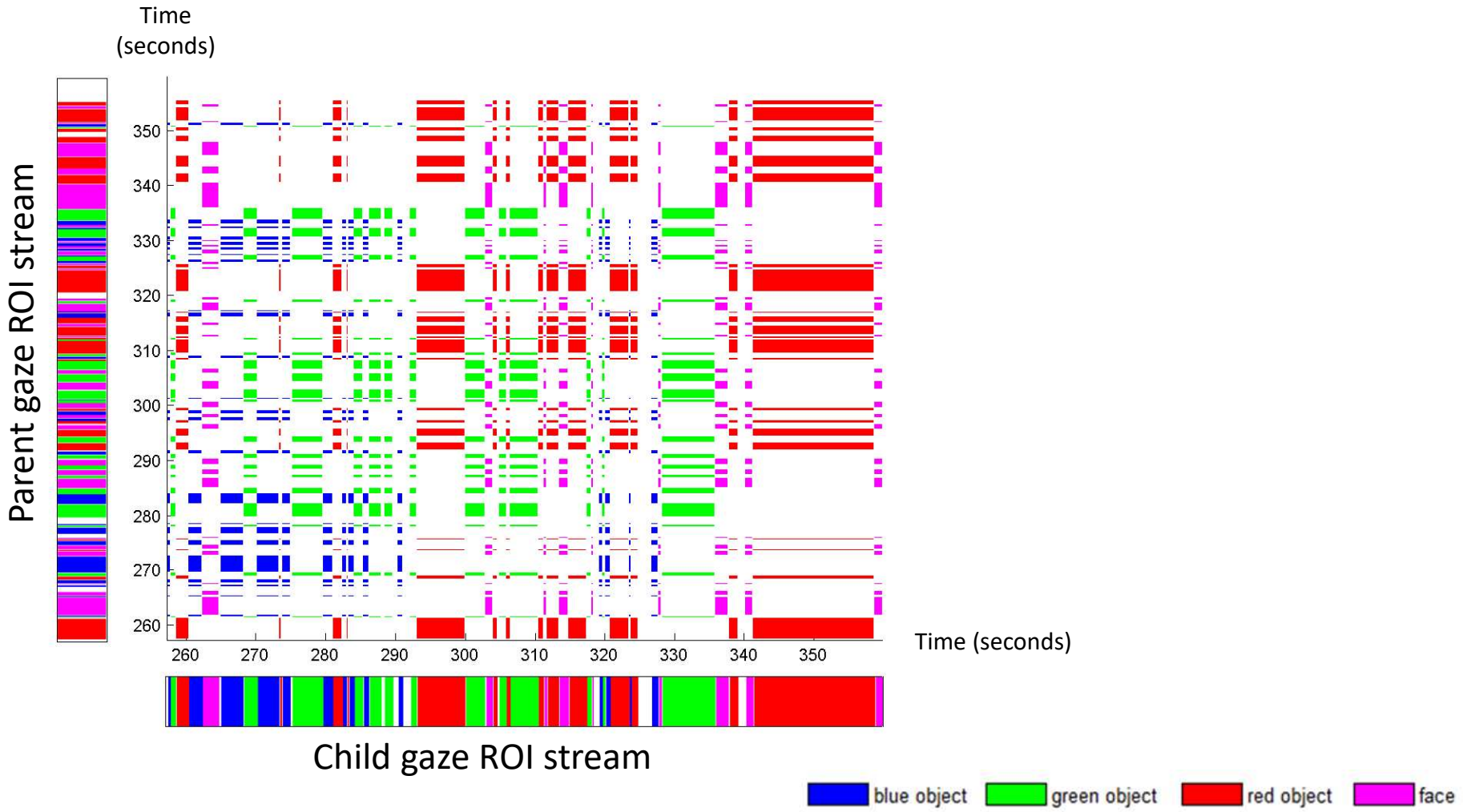


Every CRP can be economically stored as a list of *CRB*s:

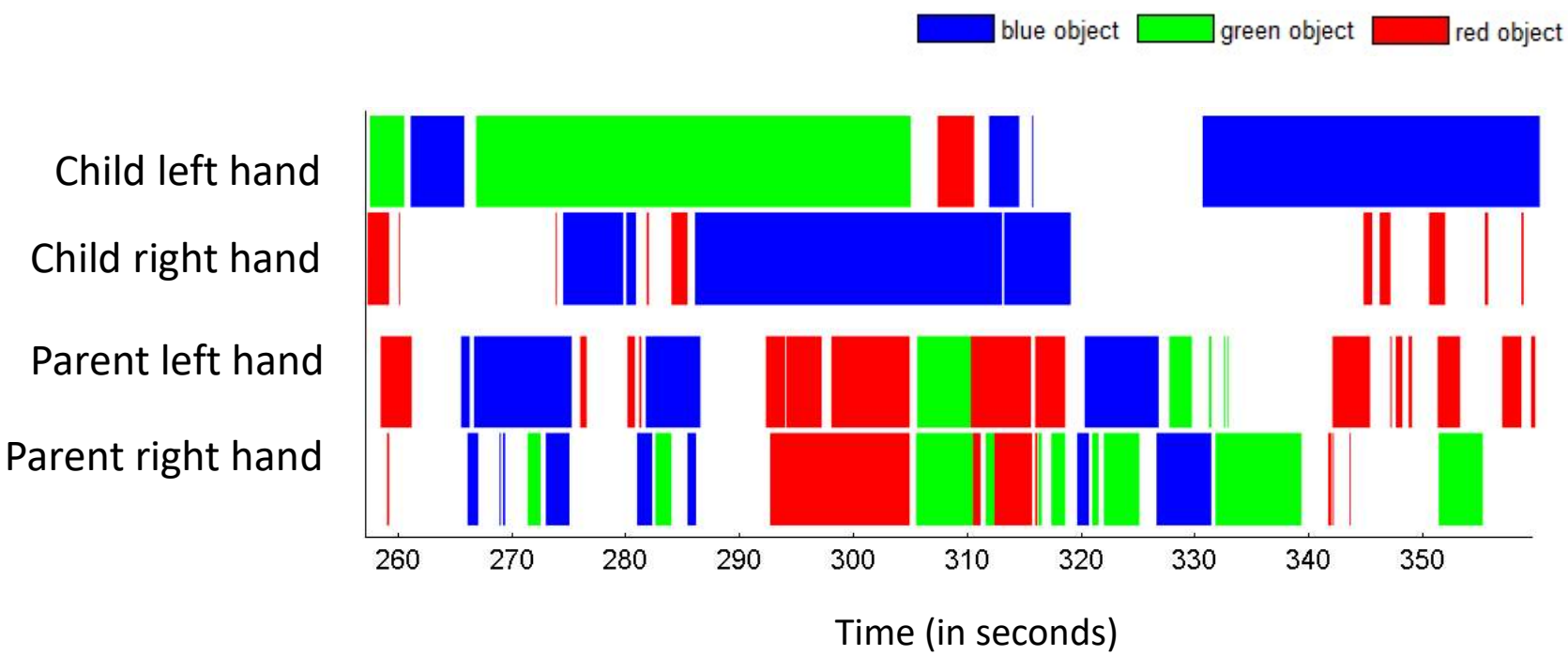
$$\{CRB_1, CRB_2 \ldots CRB_k\}$$

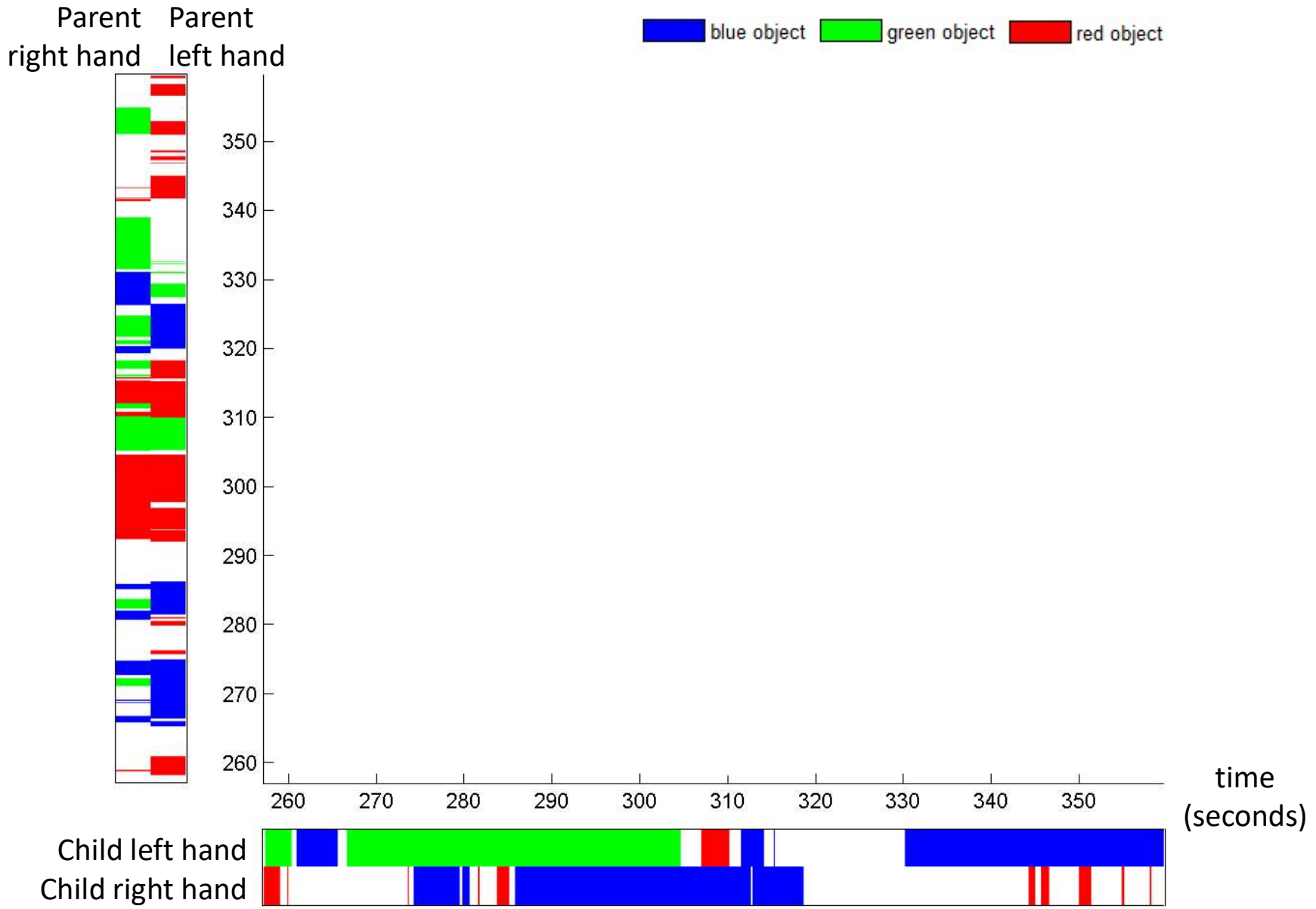


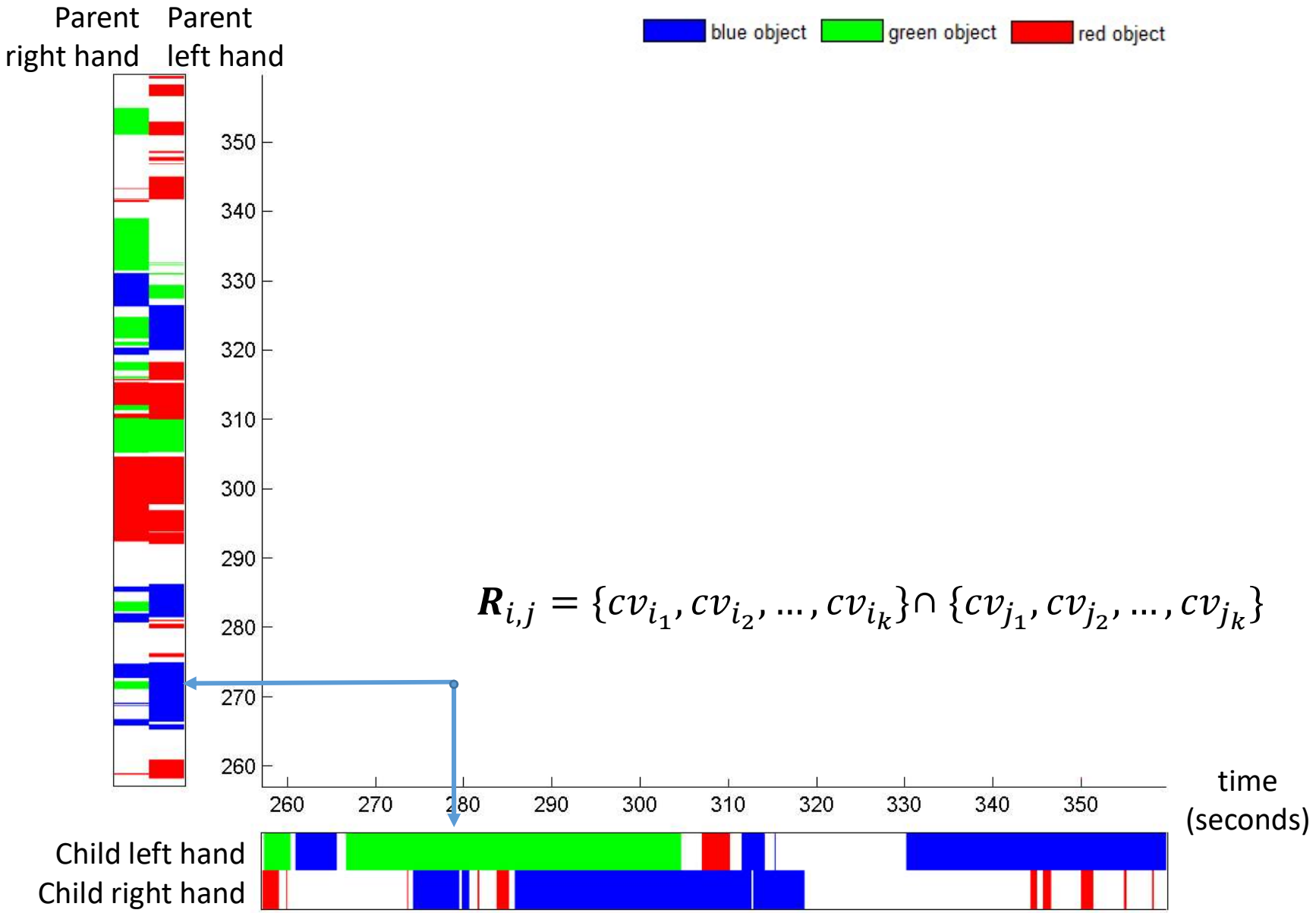
With matrix data structure, CRP can only reflect the interaction dynamics between two time series.



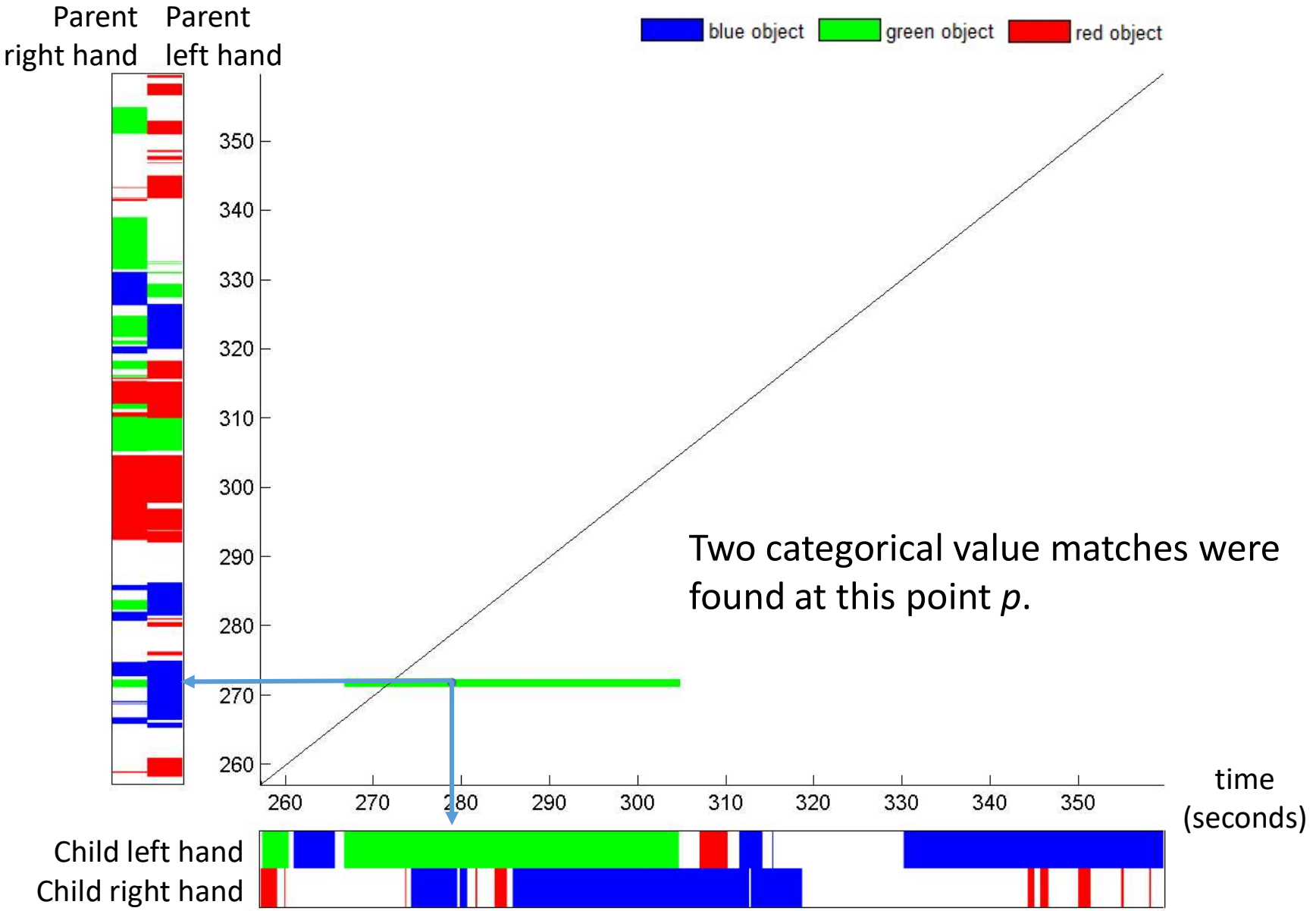
Construct Cross Recurrence Plot with four holding behavioral data streams

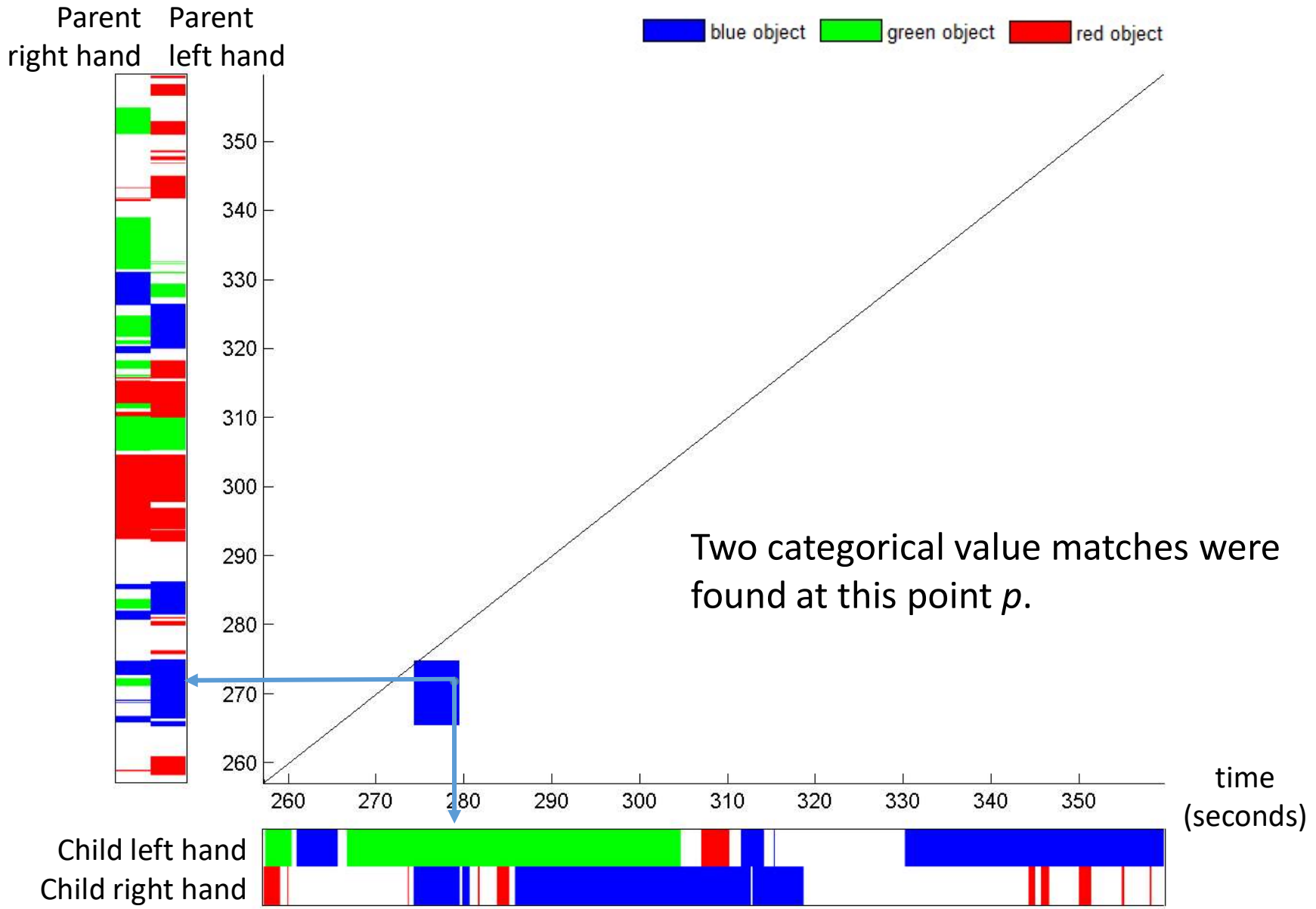


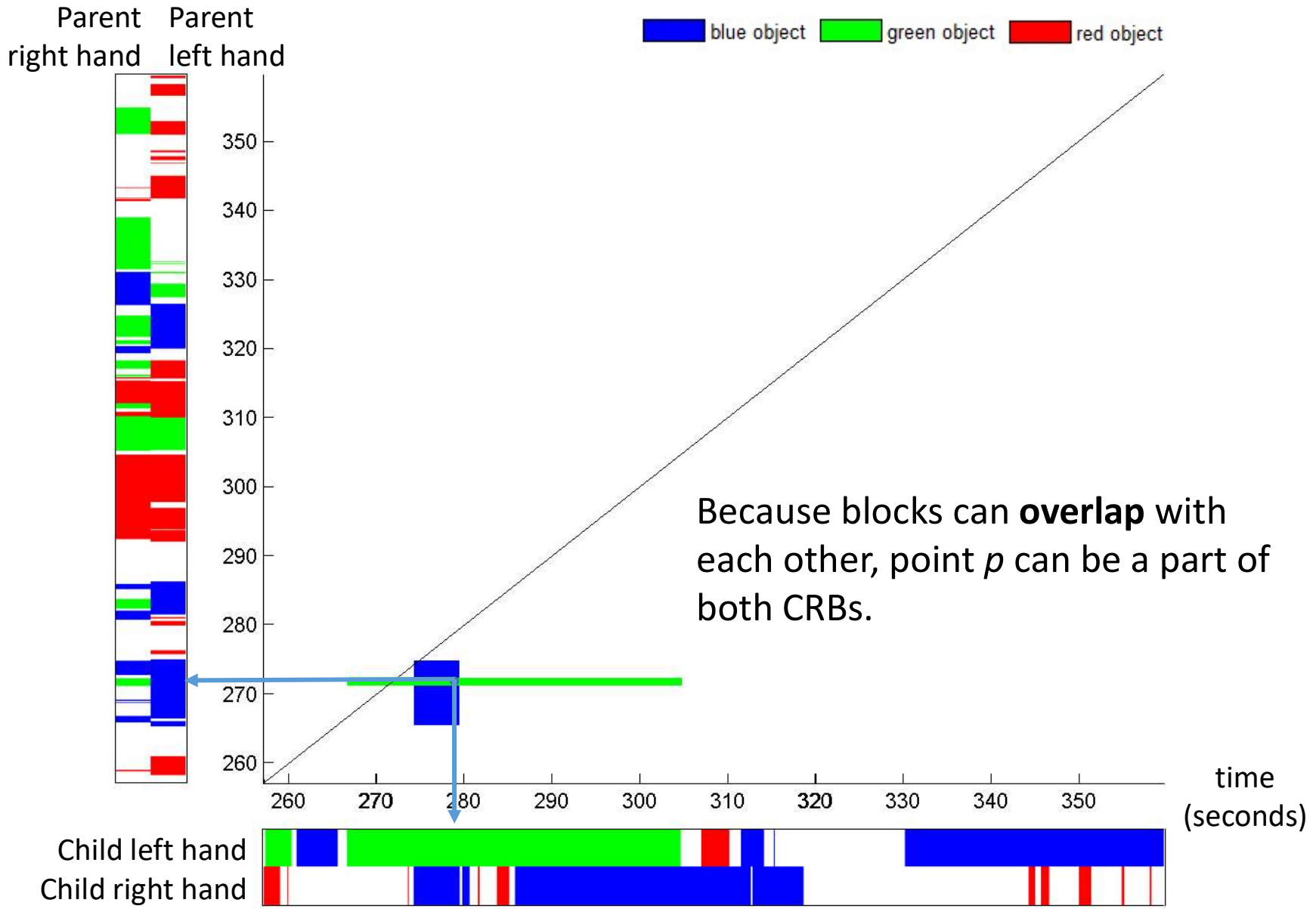

Parent right hand
Parent left hand
blue object
green object
red object
350
340
330
320
310
300
290
280
270
260
260
270
280
290
300
310
320
330
340
350
time (seconds)
Child left hand
Child right hand



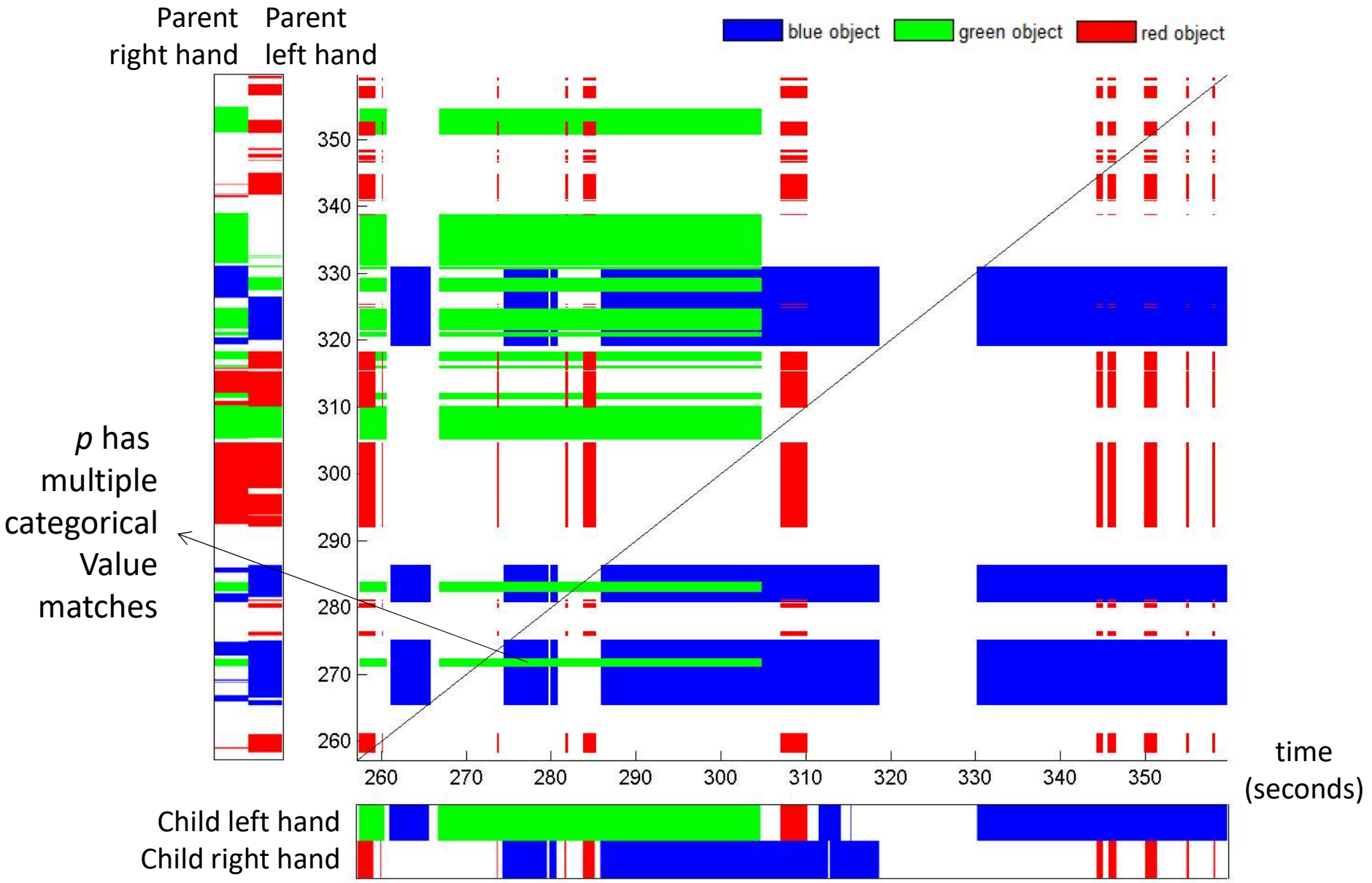
$$\boldsymbol{R}_{i,j} = \{cv_{i_1}, cv_{i_2}, \ldots, cv_{i_k}\} \cap \{cv_{j_1}, cv_{j_2}, \ldots, cv_{j_k}\}$$


Parent right hand
Parent left hand
blue object
green object
red object
350
340
330
320
310
300
290
280
270
260
260
270
280
290
300
310
320
330
340
350
time (seconds)
Child left hand
Child right hand
Two categorical value matches were found at this point *p*.


Parent right hand
Parent left hand
blue object
green object
red object
350
340
330
320
310
300
290
280
270
260
260
270
280
290
300
310
320
330
340
350
time (seconds)
Two categorical value matches were found at this point *p*.
Child left hand
Child right hand

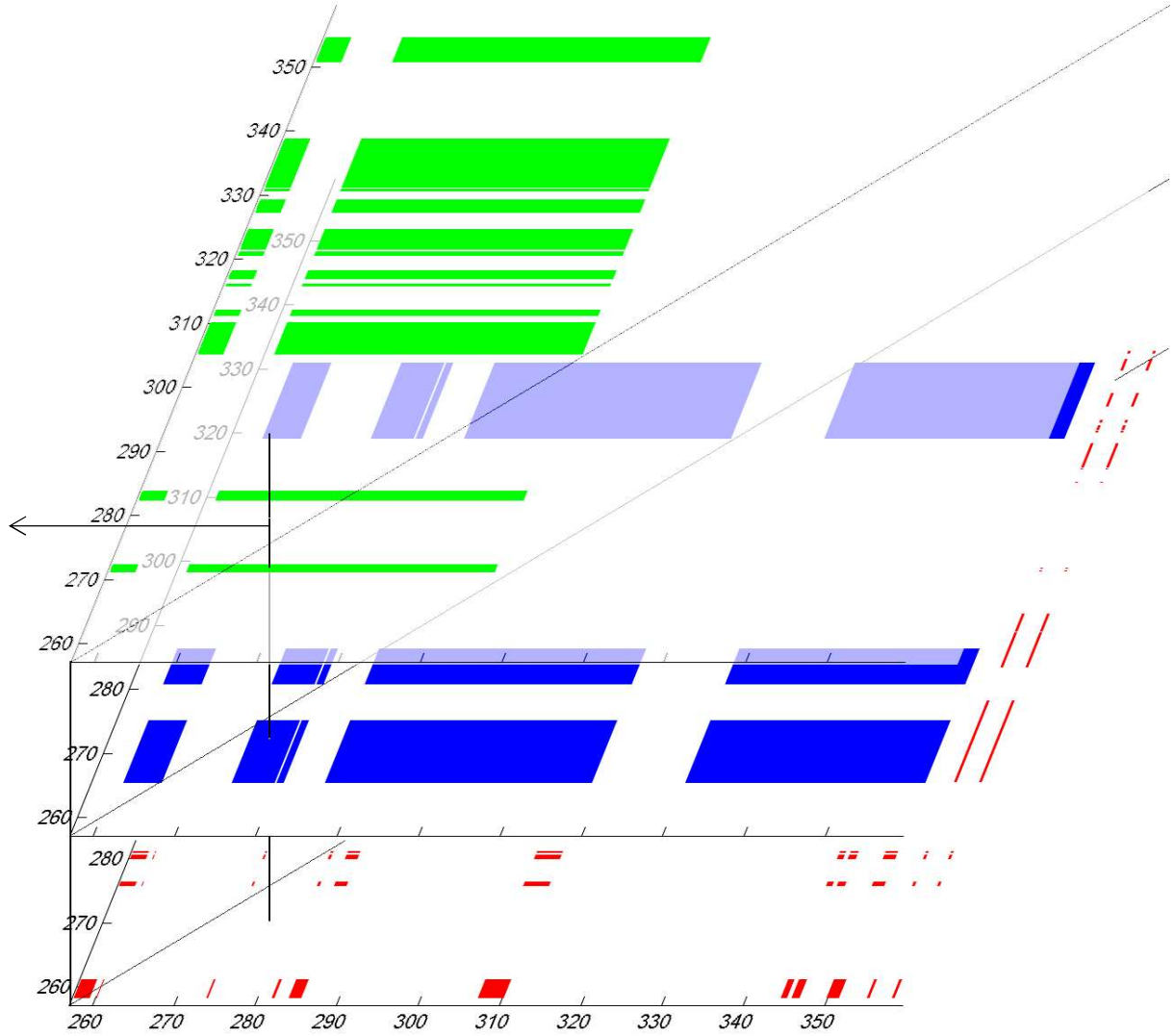


Because blocks can **overlap** with each other, point *p* can be a part of both CRBs.


Parent right hand
Parent left hand
blue object
green object
red object
p has multiple categorical Value matches
350
340
330
320
310
300
290
280
270
260
260
270
280
290
300
310
320
330
340
350
time (seconds)
Child left hand
Child right hand

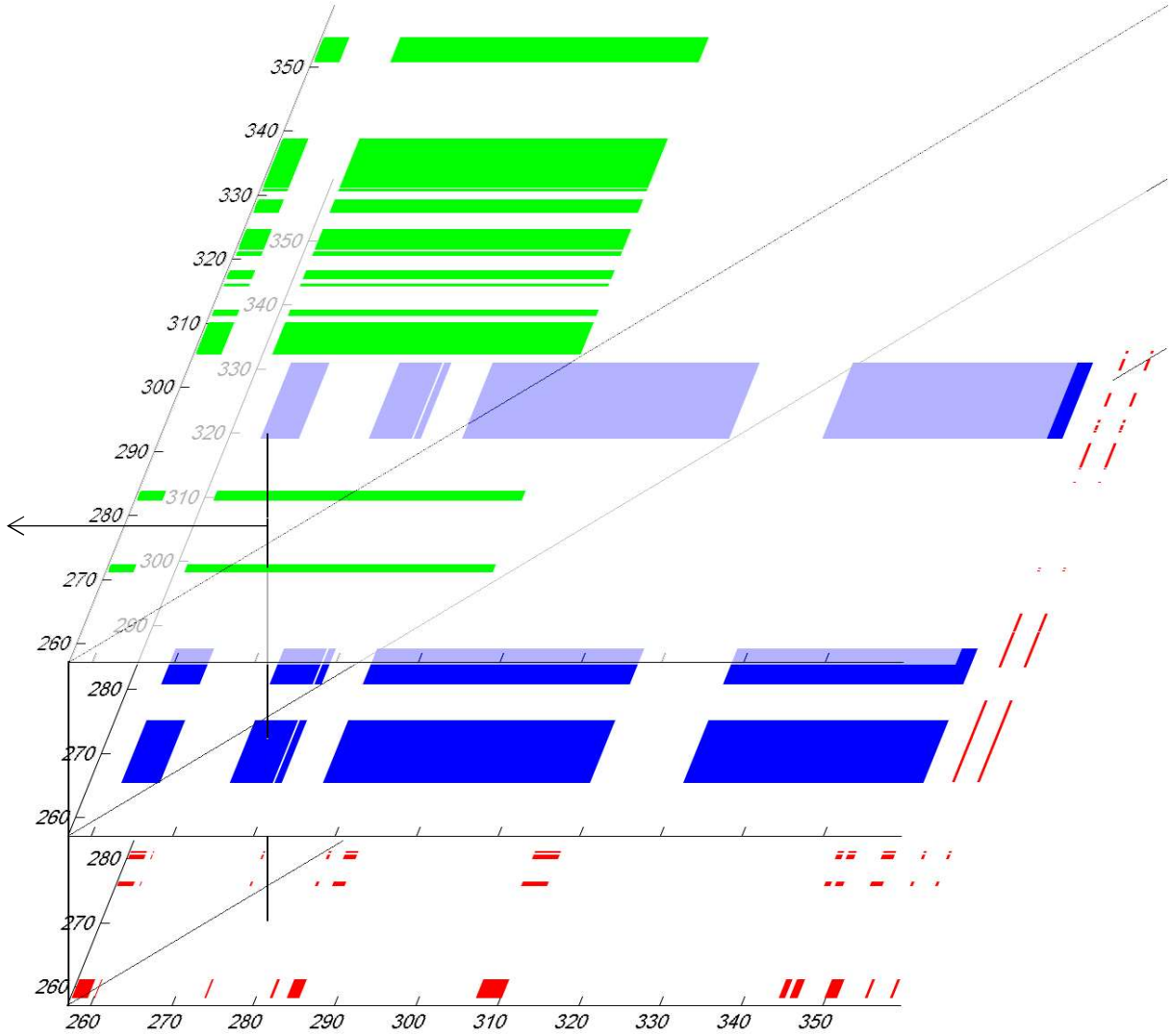
Three possible state matches

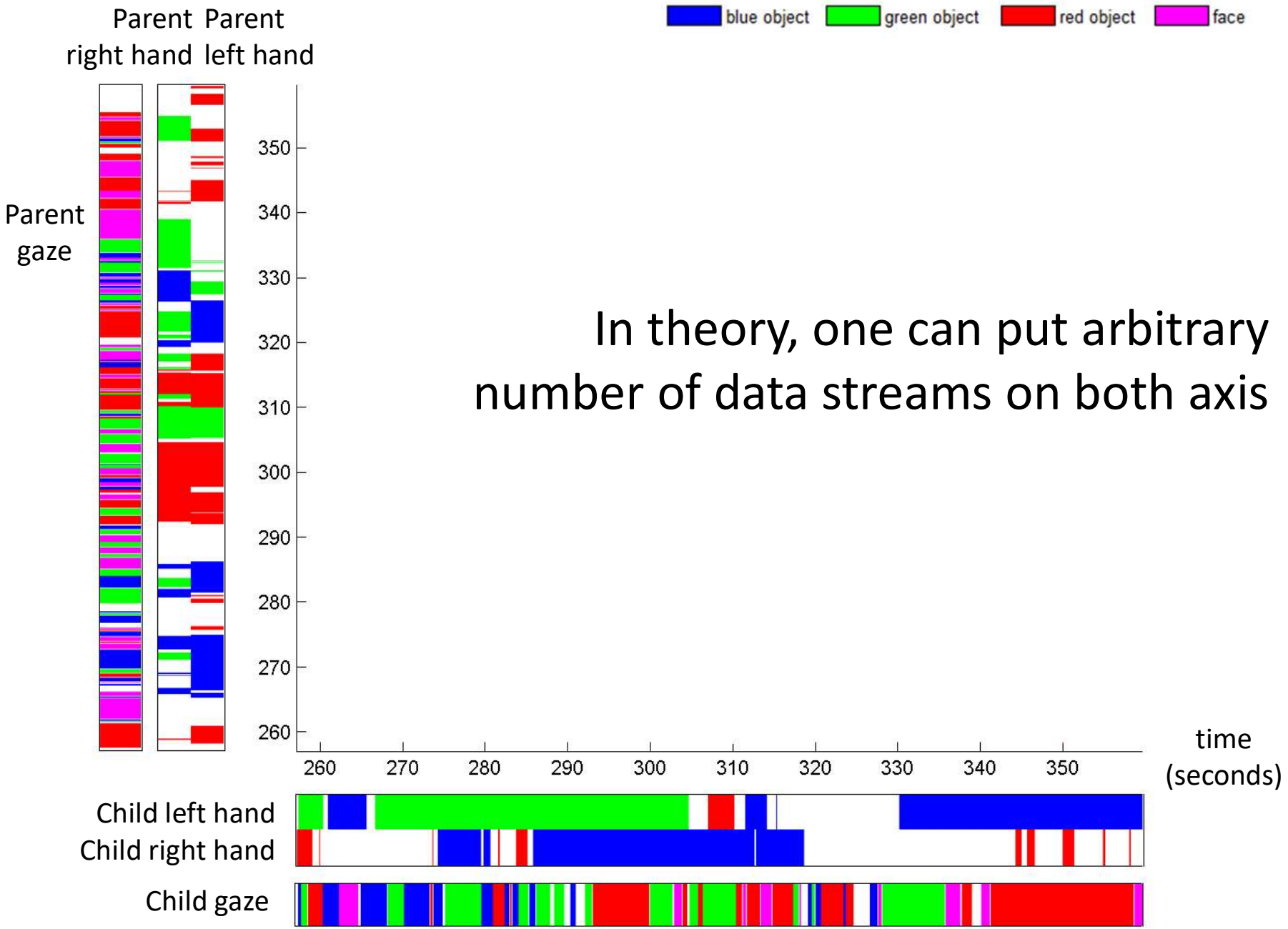
Point *p* has multiple categorical value matches



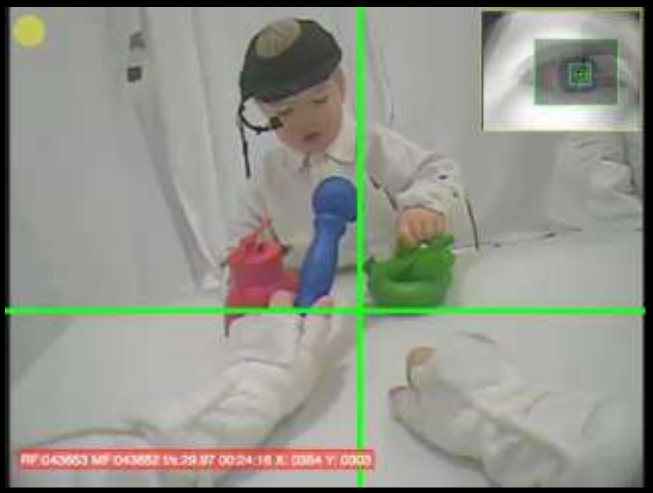
Cross Recurrence Block (CRB) representation allows ***multiple state matches*** to be assigned at every point in CRP.

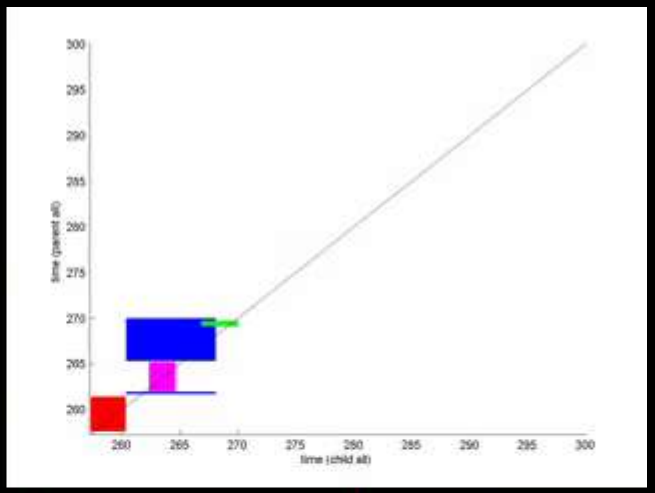
Point *p* has multiple categorical value matches





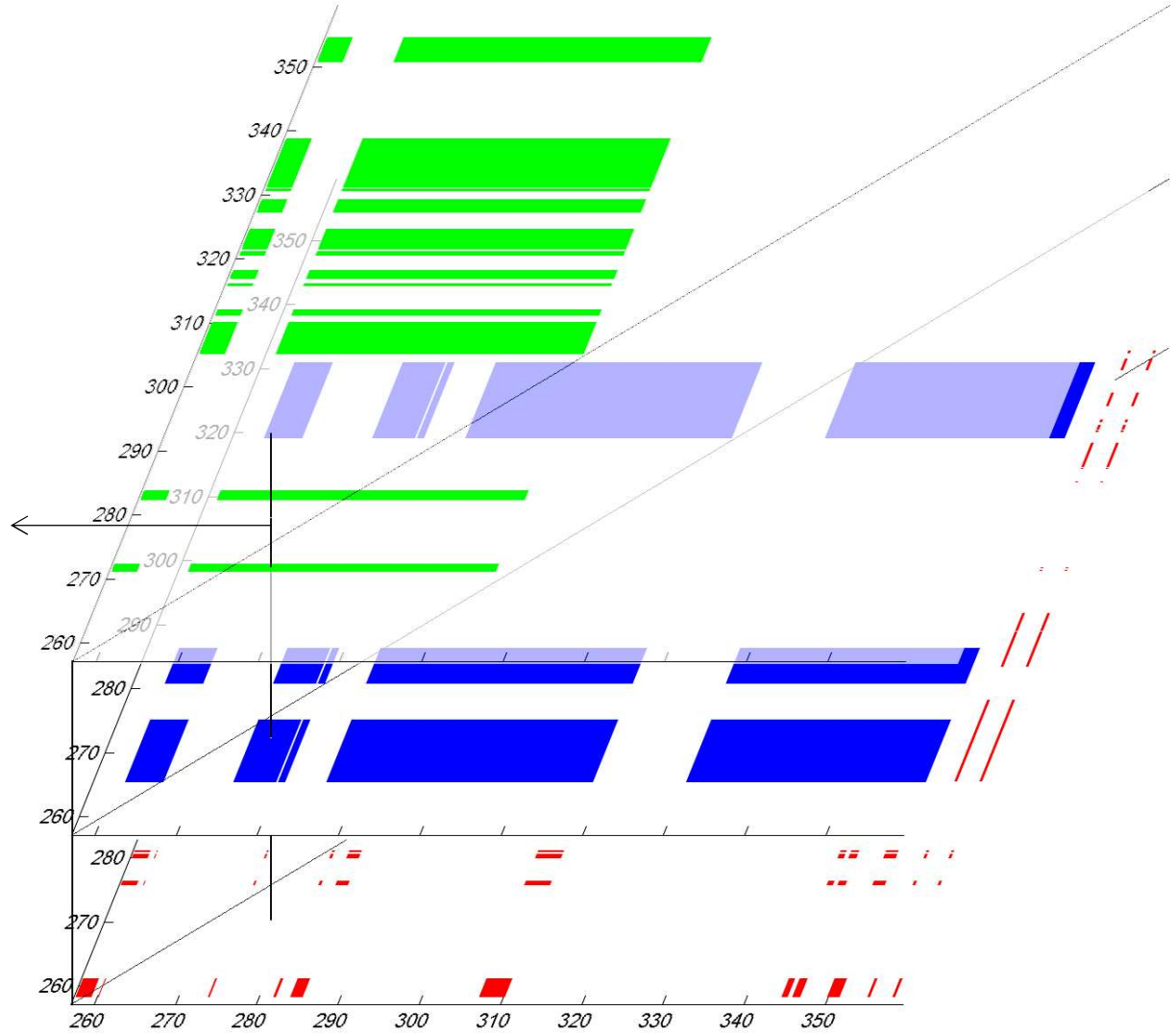
In theory, one can put arbitrary number of data streams on both axis




300
295
290
285
280
275
270
265
260
time (parent all)
260
265
270
275
280
285
290
295
300
time (child all)

It is not restricted to ROI, you can define your own state space:
1 – eye-eye coordination, 2 – hand-hand coordination

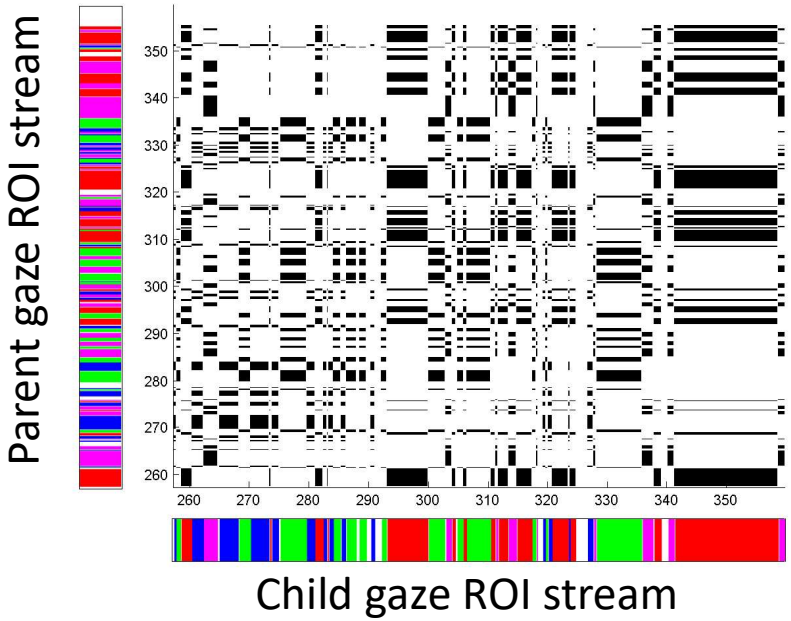
Point *p* has multiple categorical value matches

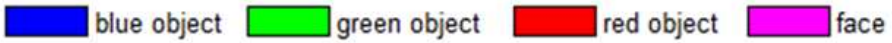


Conclusion

Conclusion

- We extended the value range of state matches to include different categorical values (with color coding) in a Cross Recurrence Plot (CRP).





Conclusion

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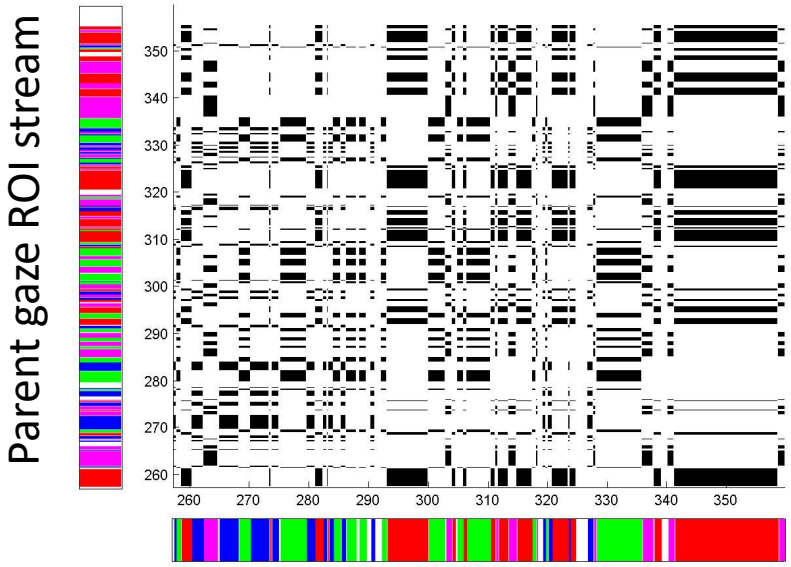
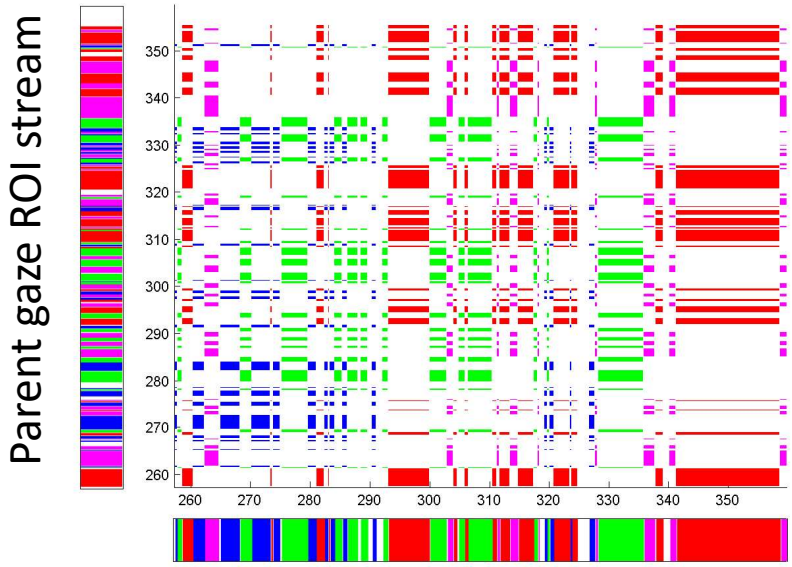
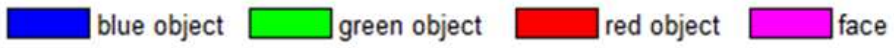
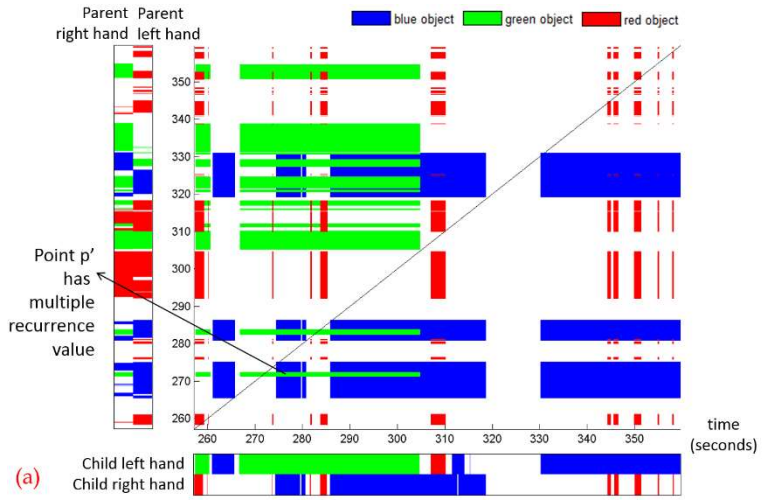


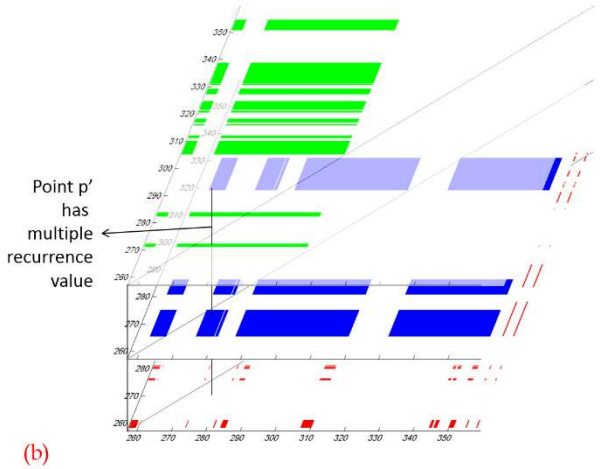




Conclusion

- **Cross Recurrence Block (CRB)** representation was introduced as a new underlying data structure of CRP, which allows CRP to capture interaction dynamics with more than two agents or behavioral modules.



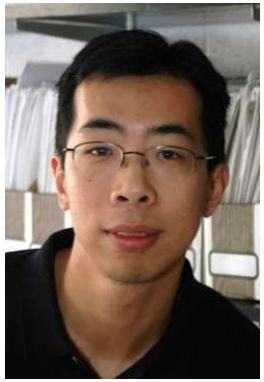


Conclusion

- **Cross Recurrence Block (CRB)** representation was introduced as a new underlying data structure of CRP, which allows CRP to capture interaction dynamics with more than two agents or behavioral modules.

- A suite of quantitative measures can be extracted based on CRBQA to reveal fine-grained coordinative patterns and describe complex interactive structures.







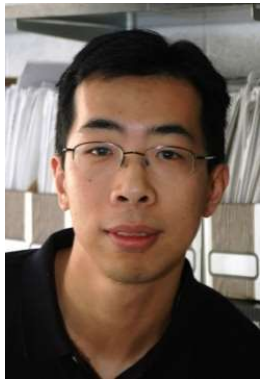




Thank you!

http://www.indiana.edu/~dll/











Questions?

http://www.indiana.edu/~dll/

Standard behavioral statistics

vs

Cross Recurrence Block based Quantification Analysis (CRBQA)

- Holding action dataset
- 12 children at 12 month olds, 12 children at 24 month olds
- Each interaction included four 1-1.5 minute long play sessions. And four holding action temporal streams (both hands from the child and the parent) were used for analysis.

Table 1. List of behavioral measures of the child's and parent's holding events between two age groups

Behavioral measure	12 month	24 month	stats
Duration of child holding (seconds)	4.67±0.51	3.42±0.43	t(23)=1.87 p=0.07
Duration of parent holding (seconds)	1.91±0.14	2.40±0.21	t(23)=-1.90 p=0.07
Frequency of child holding (per minute)	15.49±1.98	15.26±1.30	t(23)=0.09 p=0.93
Frequency of parent holding (per minute)	22.42±1.56	22.39±1.90	t(23)=0.01 p=0.99
Duration of joint holding (seconds)	0.82±0.07	10.71±0.05	t(23)=1.23 p=0.23
Joint holding Proportion of time	11.27±1.65	11.24±1.22	t(23)=0.01 p=0.99

Table 2. List of measures extracted with Cross Recurrence Block based Quantification Analysis of the child's and parent's holding events between two age groups

CRBQA	12 month	24 month	stats
Width (seconds)	11.89±2.34	7.96±1.45	t(23)=1.43 p=0.17
Height (seconds)	3.25±0.30	7.33±1.43	t(23)=-2.80 p<0.01
Frequency of horizontal CRBs (per minute)	4.51±0.56	3.82±0.33	t(23)=1.05 p=0.30
Frequency of vertical CRBs (per minute)	2.22±0.54	4.57±0.91	t(23)=-2.23 p<0.05
Start time lag (in seconds)	4.55±1.75	-0.01±1.32	t(23)=2.08 p<0.05
End time lag (in seconds)	-4.09±0.93	-0.63±1.26	t(23)=-2.21 p<0.05

Table 2. List of measures extracted with Cross Recurrence Block based Quantification Analysis of the child's and parent's holding events between two age groups

CRBQA	12 month	24 month	stats
Width (seconds)	11.89±2.34	7.96±1.45	t(23)=1.43 p=0.17
Height (seconds)	3.25±0.30	7.33±1.43	t(23)=-2.80 p<0.01
Frequency of horizontal CRBs (per minute)	4.51±0.56	3.82±0.33	t(23)=1.05 p=0.30
Frequency of vertical CRBs (per minute)	2.22±0.54	4.57±0.91	t(23)=-2.23 p<0.05
Start time lag (in seconds)	4.55±1.75	-0.01±1.32	t(23)=2.08 p<0.05
End time lag (in seconds)	-4.09±0.93	-0.63±1.26	t(23)=-2.21 p<0.05

Table 2. List of measures extracted with Cross Recurrence Block based Quantification Analysis of the child's and parent's holding events between two age groups

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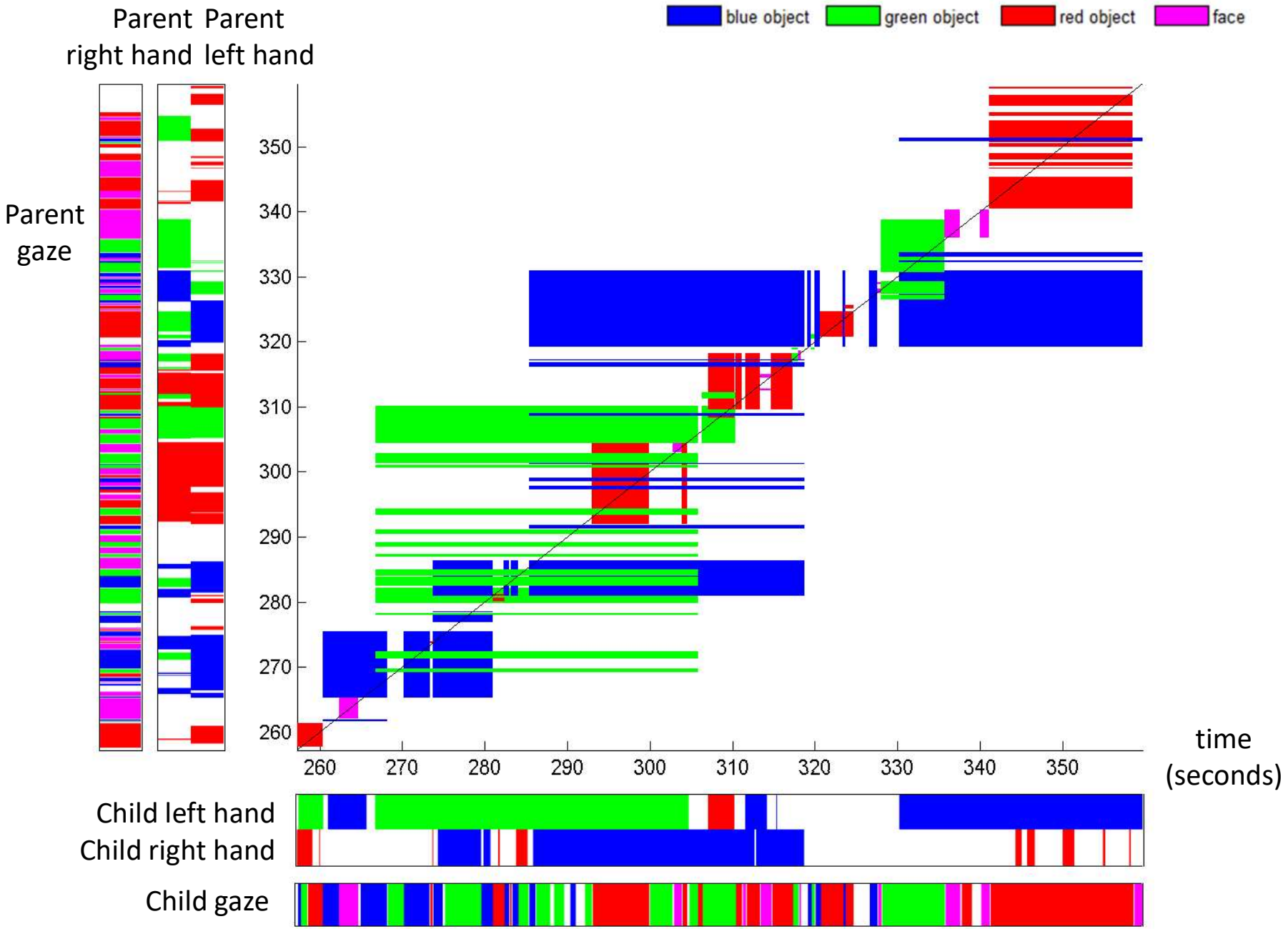
blue object
green object
red object
face
Parent right hand
Parent left hand
Parent gaze
350
340
330
320
310
300
290
280
270
260
260
270
280
290
300
310
320
330
340
350
time (seconds)
Child left hand
Child right hand
Child gaze