Chimpanzee Gesture Ngrams

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11-11-2024

Contents

1 Predictability of next elements in chimpanzee gesture sequences

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1.1 Abstract

Abstract Recent research has produced evidence for basic combinatorial abilities in the vocal systems of different animal species. Here, we investigate the structure of gesture sequences in Eastern chimpanzees (Pan troglodytes schweinfurthii) to detect whether gestural communication shows non-random combinations and how combinatorial rules influence predictability. As the parsing of signals into sequences is dependent on researcher decisions, we employ a multiverse approach, considering four different definitions of what constitutes a 'sequence' based on varying time thresholds. Our results indicate that sequences tend to be short (even with the most liberal time window) and that transitions between some gesture types occur more frequently than expected by chance, with some transitions showing significant association across all time windows. These transitions often involve repetition, suggesting persistence as a key aspect of chimpanzee gestural sequences. Information about previous gestures reduced uncertainty in predicting subsequent gestures. The order of gestures within sequences appears to be less critical than their cooccurrence, challenging assumptions based on the linear patterning derived from vocal communication. The findings highlight the importance of methodological choices in sequence definition and suggest that chimpanzee gestural communication is characterised by a mix of predictability and flexibility, with implications for understanding the evolution of complex communication systems.

2 Information

The code provided below should enable researchers to replicate all results in this study. All functions are defined initially in this document, rather than standalone functions - use the Table of Content to navigate.

3 Set options

4 Set Libraries

5 Load Data

We have four datasets, each with a different time threshold for defining a sequence. We will load all datasets. They are consistently labelled as '_5sec' (5 second time threshold), '_rapid' (based on rapid sequence definitions), '_overlap' (overlapping sequences), and '_solitary' (solitary gestures).

6 Markov transitions

6.1 N-Grams

The following functions take the sequence objects, calculate the probabilities of elements transitioning into each other, and then bootstrap the data to check the stability of the conditional probabilities and their significance compared to random.

6.2 Functions

6.2.1 Calculate N-grams

This function will calculate the probabilities of AB, ABC, and ABCD.

6.2.2 Bootstraps

This function bootstraps the n-grams to check for data quality.

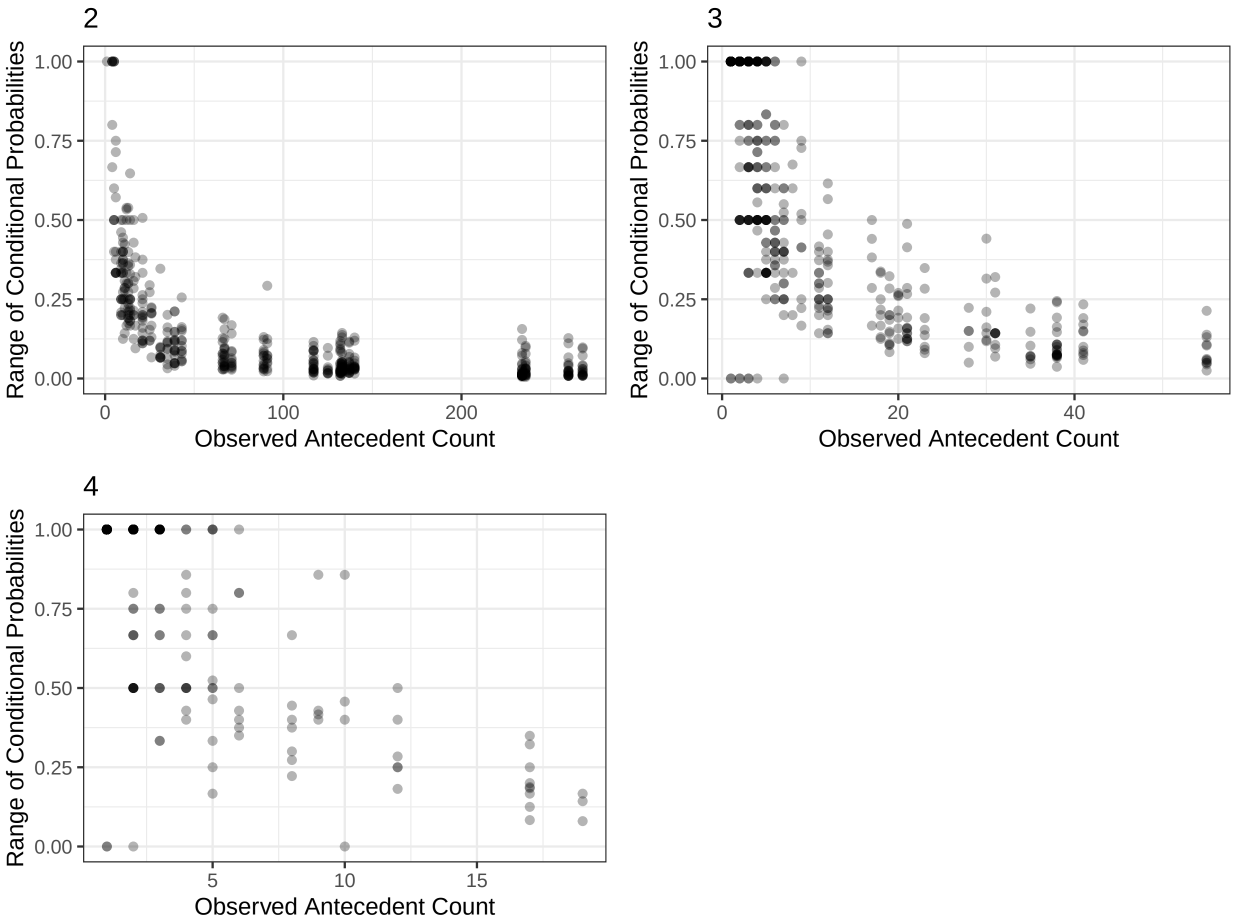
6.2.3 Calculate 2,3, and 4-Grams

Here, we apply the n-gram function to the dataset.

6.3 Bootstrap N-grams

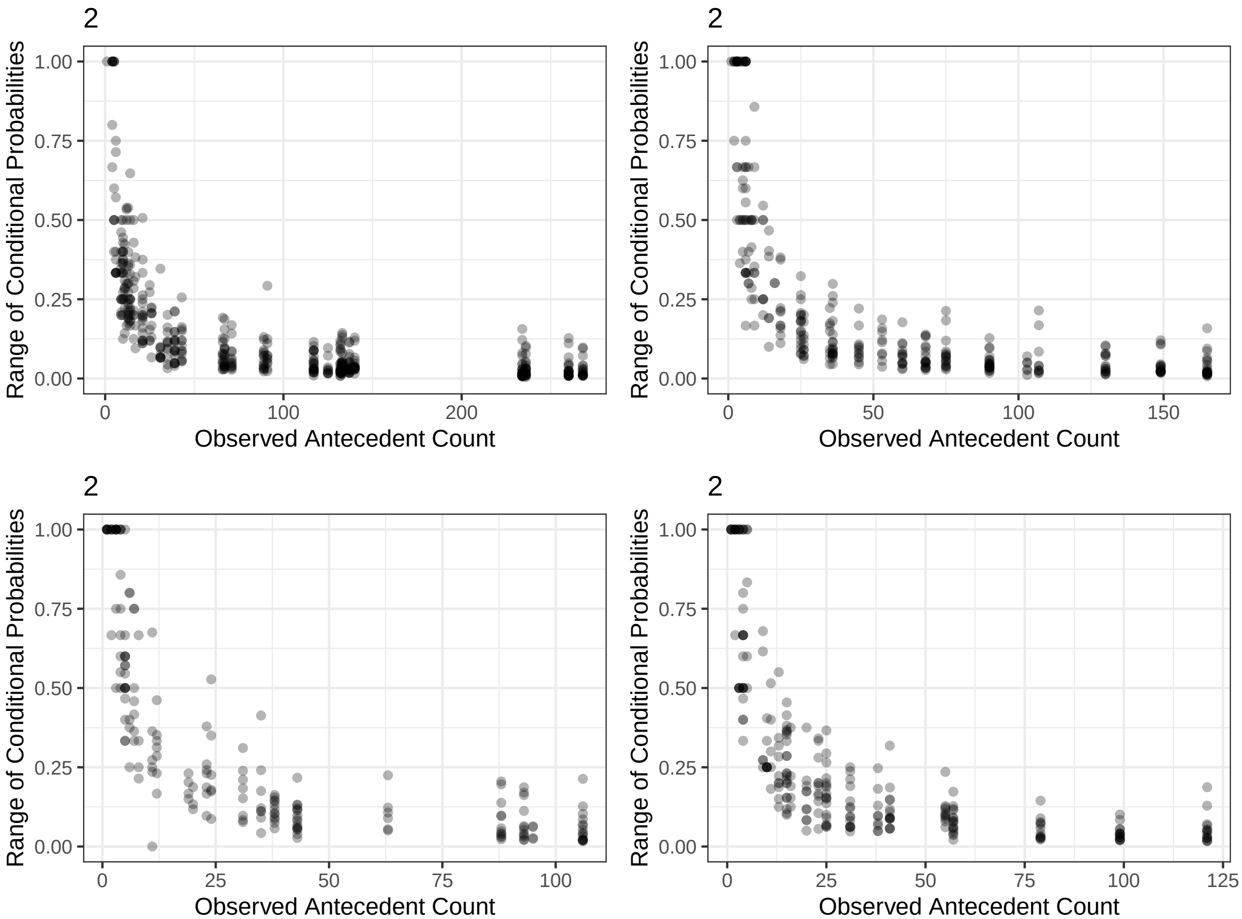
Here, we bootstrap the data and calculate the conditional probabilities to check how stable the conditional probabilities are. Set n to 1000

Now, we plot the distribution of the range of bootstrapped conditional probabilities, with the frequency of the consequent element on the x-axis and the probability range on the y-axis.



Even for 3-grams (two antecedents predicting third element) the conditional probabilities are highly unstable. We need to drop 4-grams, the conditional probabilities are all over the place.

Let's look at the different time intervals together.



Interestingly, all follow a similar pattern (rare antecedents have unpredictable probabilities, with increasing sample size there is increasing stability), but the inflection points occur at different sample sizes, indicating that, if we had the same sample size, maybe the different would not have similar stability. We can actually check that by testing the re-test reliability of each given different sample sizes.

7 Significant N-grams

We establish which gesture transitions are significant by randomising the gesture tokens, while keeping the gesture probability and the sequence lengths the same.

7.1 Functions

7.1.1 Shuffle sequences for significance on different levels

Make a function to shuffle sequences while controlling sequence length.

7.1.2 Networks

7.2 Generate significance values

Here, we generate the significance values for the different time frames. We will use the bootstrapped data to check the significance of the observed conditional probabilities.

7.2.1 List significant ngrams

Make a list of the significant n-grams of all levels for the Full Sequences at 5 seconds. Change the time frame to see the significance there.

```
##                                         antecedent      consequent count
## 1           StompObject,StompObject,StompObject     StompObject     5
## 2                 HitObject,HitObject,HitObject       HitObject     6
## 3                                Push,Push,Push            Push     7
## 4                    HitOther,HitOther,HitOther        HitOther     5
## 5                             Reach,Reach,Reach           Reach    10
## 6                                Pull,Pull,Pull            Pull    17
## 7               HitObject,StompObject,HitObject     StompObject     6
## 8  BigLoudScratch,BigLoudScratch,BigLoudScratch  BigLoudScratch     5
## 9                 BigLoudScratch,BigLoudScratch  BigLoudScratch    21
## 10                        HitObject,StompObject     StompObject     9
## 11                      ObjectShake,ObjectShake       HitObject     8
## 12                          HitObject,HitObject       HitObject    20
## 13                        HitObject,StompObject       HitObject    11
## 14                      ObjectShake,ObjectShake      ObjectMove     5
## 15                      ObjectShake,ObjectShake     ObjectShake    23
## 16                      ObjectShake,StompObject     ObjectShake     6
## 17                      StompObject,StompObject     ObjectShake     5
## 18                      StompObject,StompObject     StompObject    13
## 19                        ObjectMove,ObjectMove      ObjectMove     5
## 20                        HitObject,ObjectShake     ObjectShake     8
## 21                       ObjectMove,ObjectShake     ObjectShake     5
## 22                      StompObject,StompObject       HitObject     9
## 23                        StompObject,HitObject       HitObject    11
## 24                        ObjectShake,HitObject     ObjectShake     6
## 25                      ObjectShake,ObjectShake            Jump     6
## 26                          HitObject,HitObject     ObjectShake     5
## 27                        HitObject,ObjectShake       HitObject     5
## 28                                    Push,Push            Push    16
## 29                        StompObject,HitObject     StompObject    11
## 30                                  Fling,Fling           Fling     7
## 31                            HitOther,HitOther        HitOther    12
## 32                                  Touch,Touch           Touch    13
## 33                          HitObject,HitObject     StompObject     7
```

```
## 34                  Reach,Reach          Reach   26
## 35                    Pull,Pull           Pull   24
## 36                    Grab,Grab           Grab    5
## 37       Present,BigLoudScratch BigLoudScratch    6
## 38       BigLoudScratch,Present BigLoudScratch   16
## 39 BigLoudScratch,BigLoudScratch        Present    9
## 40               BigLoudScratch BigLoudScratch  122
## 41                      Present BigLoudScratch  107
## 42                   ObjectMove     ObjectMove   33
## 43                       Stroke         Stroke    7
## 44                      Embrace           Bite   16
## 45                         Push           Push   49
## 46                    HitObject    StompObject   52
## 47                  StompObject    StompObject   70
## 48                   ObjectMove    StompObject   16
## 49                  ObjectShake    ObjectShake  122
## 50                  ObjectShake      HitObject   29
## 51                    HitObject     ObjectMove   11
## 52                        Reach          Reach   89
## 53                        Reach          Touch   16
## 54                        Swing      HitObject    9
## 55                    HitObject      HitObject   77
## 56               BigLoudScratch        Present   84
## 57                        Touch          Touch   63
## 58                  StompObject      HitObject   64
## 59               BigLoudScratch           Pull    8
## 60                        Shake          Shake    8
## 61                         Pull           Pull   40
## 62                    HitObject           Jump    9
## 63                         Jump      HitObject    7
## 64                    HitObject          Swing    9
## 65                        Swing       HitOther   11
## 66                  ObjectShake     ObjectMove   20
## 67                      Rocking    ObjectShake    5
## 68                  ObjectShake        Rocking    6
## 69                   ObjectMove    ObjectShake   24
## 70                  ObjectShake           Jump    8
## 71                         Jump    ObjectShake    6
## 72                         Push          Touch   15
## 73                  StompObject     ObjectMove   14
## 74                   ObjectMove      HitObject   16
## 75                        Touch          Reach    7
## 76                    HitObject       HitOther    9
## 77                  StompObject          Swing   12
## 78                        Fling          Fling   21
```

```
## 79                                              StompObject     ObjectShake   19
## 80                                              ObjectShake     StompObject   35
## 81                                                   Dangle           Swing   28
## 82                                                     Bite        HitOther    6
## 83                                                    Touch        GrabHold    7
## 84                                                     Grab            Bite   18
## 85                                              StompObject          Dangle   10
## 86                                                    Swing           Shake    5
## 87                                                 GrabHold            Bite   18
## 88                                                    Swing          Dangle   13
## 89                                                    Shake           Swing    5
## 90                                                 HitOther            Grab   12
## 91                                                     Grab            Grab   21
## 92                                                 GrabHold            Grab    7
## 93                                               ObjectMove           Swing    9
## 94                                                    Swing           Swing   24
## 95                                                    Swing      ObjectMove    9
## 96                                               ObjectMove           Shake    5
## 97                                               ObjectMove     ThrowObject    5
## 98                                                HitObject     ObjectShake   33
## 99                                                    Swing     ObjectShake   12
## 100                                                   Swing     StompObject   10
## 101                                             ObjectShake           Swing   15
## 102                                             StompObject        HitOther    7
## 103                                             StompObject       HeadStand    5
## 104                                                  Dangle       HitObject   13
## 105                                               HitObject          Dangle    5
## 106                                                  Dangle     StompObject    5
## 107                                                    Bite            Bite   10
## 108                                         PresentGenitals PresentGenitals    9
## 109                                                   Touch            Push    9
## 110                                                    Grab        HitOther    7
## 111                                                HitOther        HitOther   52
## 112                                                    Pull            Push    7
## 113                                               HitObject           Reach    5
## 114                                                   Raise           Touch    6
## 115                                                   Reach           Raise    6
## 116                                                   Raise           Reach    6
## 117                                                   Raise           Raise   10
## 118                                                  Dangle          Dangle    6
## 119                                                    Grab           Touch    7
## 120                                                   Touch            Bite    8
## 121                                                   Touch        HitOther    5
## 122                                                LeafClip        LeafClip   10
## 123                                                  Dangle        HitOther   13
```

```
## 124                                       HitOther           Swing    8
## 125                                           Grab        GrabHold    6
## 126                                       HitOther          Dangle    5
## 127                                         Dangle            Grab    5
## 128                                       LeafClip     ObjectShake    5
## 129                                       HitOther        GrabHold    5
## 130                                       HitOther      StompOther    8
## 131                                          Touch            Grab    5
## 132                                          Raise     StompObject    5
## 133                                           Pull           Touch    5
## 134                                          Raise  BigLoudScratch   23
## 135                                      HitObject  BigLoudScratch    6
## 136                                          Touch           Raise    7
## 137                                 BigLoudScratch           Raise   14
## 138                                 BigLoudScratch            Push   14
## 139                                 BigLoudScratch PresentGenitals    5
## 140                                           Push           Raise    6
##     conditional_probability specificity expected pvalue level
## 1                0.62500000  0.09259259        0      0     4
## 2                0.50000000  0.09375000        0      0     4
## 3                0.70000000  0.30434783        0      0     4
## 4                0.83333333  0.17857143        0      0     4
## 5                1.00000000  0.50000000        0      0     4
## 6                0.89473684  0.54838710        0      0     4
## 7                0.66666667  0.11111111        0      0     4
## 8                0.62500000  0.31250000        0      0     4
## 9                0.55263158  0.31343284        0      0     3
## 10               0.29032258  0.08653846        0      0     3
## 11               0.14545455  0.06250000        0      0     3
## 12               0.48780488  0.15625000        0      0     3
## 13               0.35483871  0.08593750        0      0     3
## 14               0.09090909  0.10000000        0      0     3
## 15               0.41818182  0.19658120        0      0     3
## 16               0.35294118  0.05128205        0      0     3
## 17               0.13157895  0.04273504        0      0     3
## 18               0.34210526  0.12500000        0      0     3
## 19               0.26315789  0.10000000        0      0     3
## 20               0.44444444  0.06837607        0      0     3
## 21               0.41666667  0.04273504        0      0     3
## 22               0.23684211  0.07031250        0      0     3
## 23               0.36666667  0.08593750        0      0     3
## 24               0.30000000  0.05128205        0      0     3
## 25               0.10909091  0.25000000        0      0     3
## 26               0.12195122  0.04273504        0      0     3
## 27               0.27777778  0.03906250        0      0     3
```

```
## 28                0.76190476  0.34042553        0       0      3
## 29                0.36666667  0.10576923        0       0      3
## 30                1.00000000  0.50000000        0       0      3
## 31                0.57142857  0.22222222        0       0      3
## 32                0.56521739  0.34210526        0       0      3
## 33                0.17073171  0.06730769        0       0      3
## 34                0.74285714  0.57777778        0       0      3
## 35                0.85714286  0.52173913        0       0      3
## 36                0.55555556  0.19230769        0       0      3
## 37                0.66666667  0.08955224        0       0      3
## 38                0.88888889  0.23880597        0       0      3
## 39                0.23684211  0.52941176        0       0      3
## 40                0.45522388  0.43262411        0       0      2
## 41                0.85600000  0.37943262        0       0      2
## 42                0.25000000  0.31428571        0       0      2
## 43                0.50000000  0.38888889        0       0      2
## 44                0.64000000  0.18390805        0       0      2
## 45                0.53846154  0.48039216        0       0      2
## 46                0.22033898  0.23529412        0       0      2
## 47                0.29914530  0.31674208        0       0      2
## 48                0.12121212  0.07239819        0       0      2
## 49                0.46923077  0.49593496        0       0      2
## 50                0.11153846  0.11836735        0       0      2
## 51                0.04661017  0.10476190        0       0      2
## 52                0.63571429  0.69531250        0       0      2
## 53                0.11428571  0.11034483        0       0      2
## 54                0.07692308  0.03673469        0       0      2
## 55                0.32627119  0.31428571        0       0      2
## 56                0.31343284  0.85714286        0       0      2
## 57                0.45985401  0.43448276        0       0      2
## 58                0.27350427  0.26122449        0       0      2
## 59                0.02985075  0.10666667        0       0      2
## 60                0.20512821  0.21621622        0       0      2
## 61                0.60606061  0.53333333        0       0      2
## 62                0.03813559  0.31034483        0       0      2
## 63                0.26923077  0.02857143        0       0      2
## 64                0.03813559  0.06766917        0       0      2
## 65                0.09401709  0.07857143        0       0      2
## 66                0.07692308  0.19047619        0       0      2
## 67                0.35714286  0.02032520        0       0      2
## 68                0.02307692  0.37500000        0       0      2
## 69                0.18181818  0.09756098        0       0      2
## 70                0.03076923  0.27586207        0       0      2
## 71                0.23076923  0.02439024        0       0      2
## 72                0.16483516  0.10344828        0       0      2
```

```
## 73                0.05982906  0.13333333        0       0      2
## 74                0.12121212  0.06530612        0       0      2
## 75                0.05109489  0.05468750        0       0      2
## 76                0.03813559  0.06428571        0       0      2
## 77                0.05128205  0.09022556        0       0      2
## 78                0.67741935  0.60000000        0       0      2
## 79                0.08119658  0.07723577        0       0      2
## 80                0.13461538  0.15837104        0       0      2
## 81                0.31460674  0.21052632        0       0      2
## 82                0.17142857  0.04285714        0       0      2
## 83                0.05109489  0.17948718        0       0      2
## 84                0.25352113  0.20689655        0       0      2
## 85                0.04273504  0.18181818        0       0      2
## 86                0.04273504  0.13513514        0       0      2
## 87                0.41860465  0.20689655        0       0      2
## 88                0.11111111  0.23636364        0       0      2
## 89                0.12820513  0.03759398        0       0      2
## 90                0.09022556  0.17647059        0       0      2
## 91                0.29577465  0.30882353        0       0      2
## 92                0.16279070  0.10294118        0       0      2
## 93                0.06818182  0.06766917        0       0      2
## 94                0.20512821  0.18045113        0       0      2
## 95                0.07692308  0.08571429        0       0      2
## 96                0.03787879  0.13513514        0       0      2
## 97                0.03787879  0.50000000        0       0      2
## 98                0.13983051  0.13414634        0       0      2
## 99                0.10256410  0.04878049        0       0      2
## 100               0.08547009  0.04524887        0       0      2
## 101               0.05769231  0.11278195        0       0      2
## 102               0.02991453  0.05000000        0       0      2
## 103               0.02136752  0.41666667        0       0      2
## 104               0.14606742  0.05306122        0       0      2
## 105               0.02118644  0.09090909        0       0      2
## 106               0.05617978  0.02262443        0       0      2
## 107               0.28571429  0.11494253        0       0      2
## 108               0.42857143  0.33333333        0       0      2
## 109               0.06569343  0.08823529        0       0      2
## 110               0.09859155  0.05000000        0       0      2
## 111               0.39097744  0.37142857        0       0      2
## 112               0.10606061  0.06862745        0       0      2
## 113               0.02118644  0.03906250        0       0      2
## 114               0.08955224  0.04137931        0       0      2
## 115               0.04285714  0.08695652        0       0      2
## 116               0.08955224  0.04687500        0       0      2
## 117               0.14925373  0.14492754        0       0      2
```

```
## 118                 0.06741573  0.10909091        0       0      2
## 119                 0.09859155  0.04827586        0       0      2
## 120                 0.05839416  0.09195402        0       0      2
## 121                 0.03649635  0.03571429        0       0      2
## 122                 0.58823529  0.76923077        0       0      2
## 123                 0.14606742  0.09285714        0       0      2
## 124                 0.06015038  0.06015038        0       0      2
## 125                 0.08450704  0.15384615        0       0      2
## 126                 0.03759398  0.09090909        0       0      2
## 127                 0.05617978  0.07352941        0       0      2
## 128                 0.29411765  0.02032520        0       0      2
## 129                 0.03759398  0.12820513        0       0      2
## 130                 0.06015038  0.38095238        0       0      2
## 131                 0.03649635  0.07352941        0       0      2
## 132                 0.07462687  0.02262443        0       0      2
## 133                 0.07575758  0.03448276        0       0      2
## 134                 0.34328358  0.08156028        0       0      2
## 135                 0.02542373  0.02127660        0       0      2
## 136                 0.05109489  0.10144928        0       0      2
## 137                 0.05223881  0.20289855        0       0      2
## 138                 0.05223881  0.13725490        0       0      2
## 139                 0.01865672  0.18518519        0       0      2
## 140                 0.06593407  0.08695652        0       0      2
```

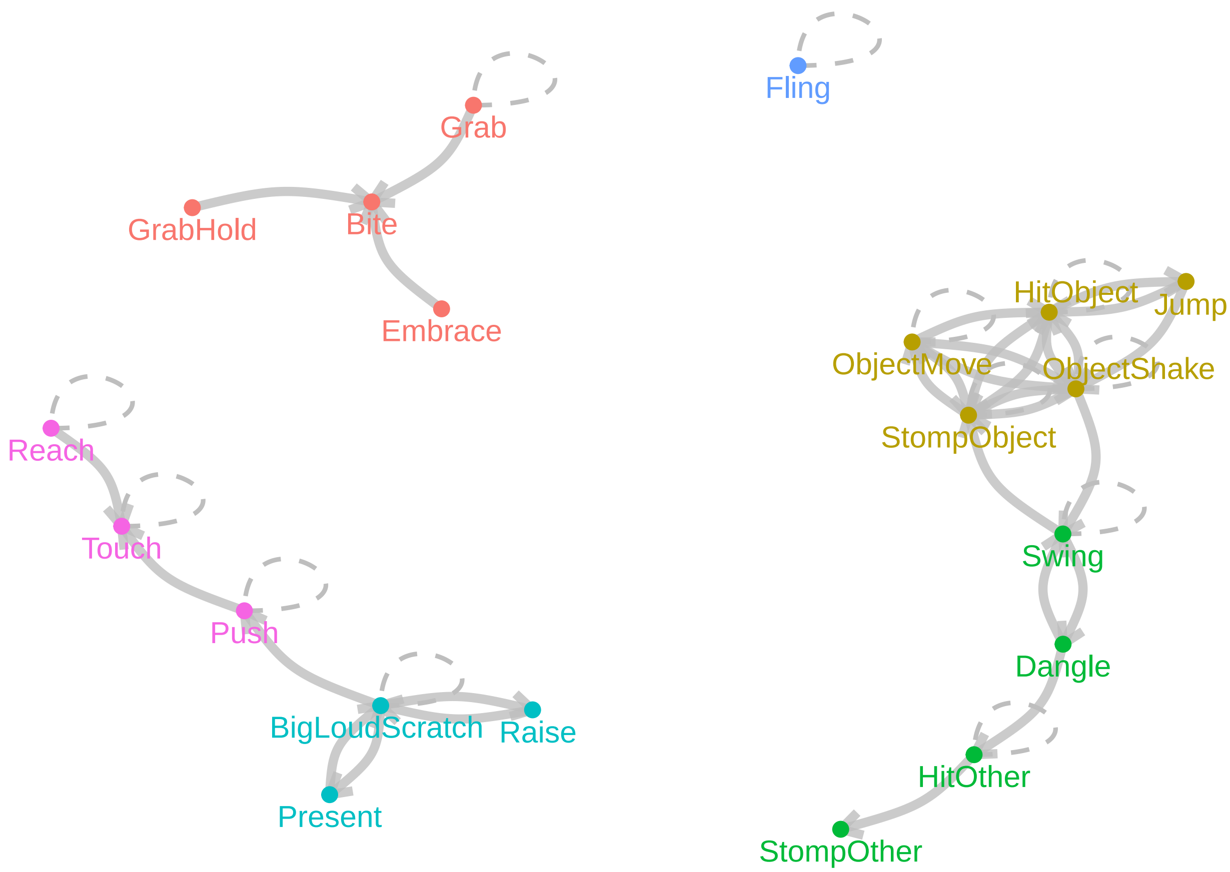
7.2.2 Make list of ngrams that are significant across time frames

Here is the table with the shared transitions across all time frames.

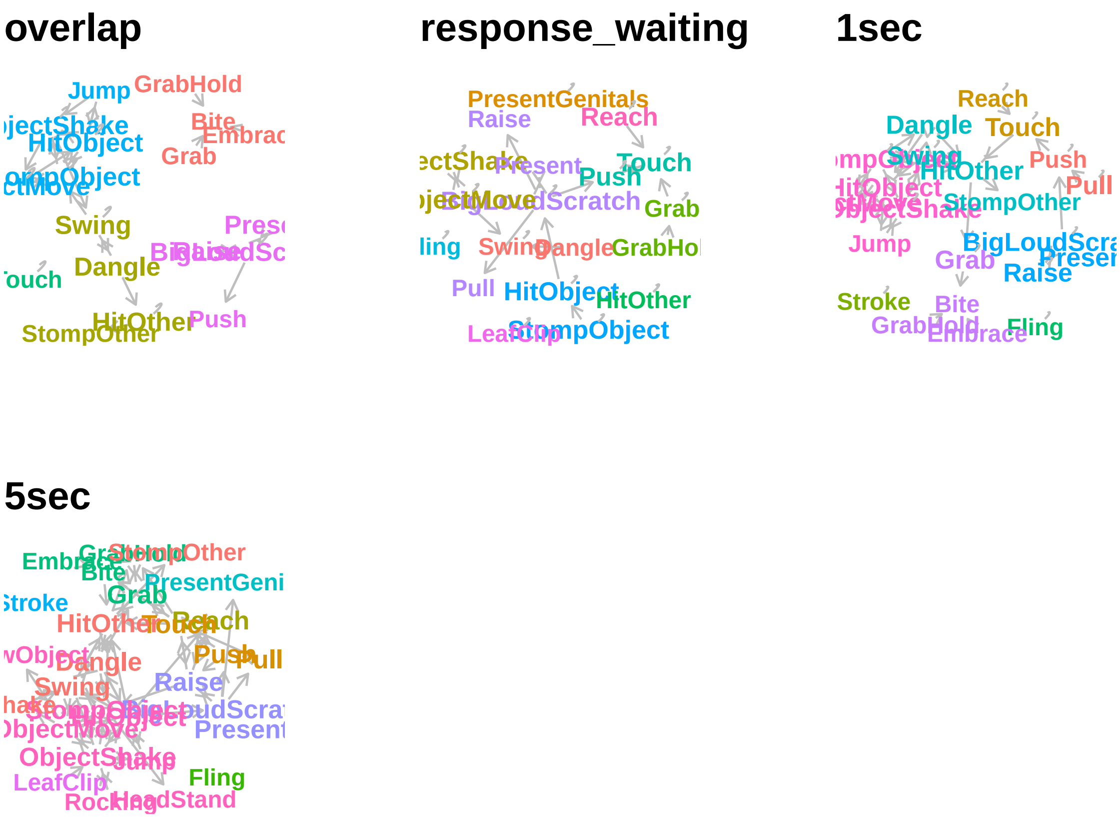
antecedent	consequent
BigLoudScratch	BigLoudScratch
Present	BigLoudScratch
BigLoudScratch	Present
ObjectMove	ObjectMove
ObjectShake	ObjectMove
BigLoudScratch	Push
HitObject	HitObject
StompObject	HitObject
StompObject	StompObject
HitOther	HitOther
ObjectShake	ObjectShake
Swing	Swing
Dangle	Swing
Touch	Touch
BigLoudScratch	Raise

Here is what the network of only the shared transitions looks like - we use 3 shared instead of 4 to be less conservative.

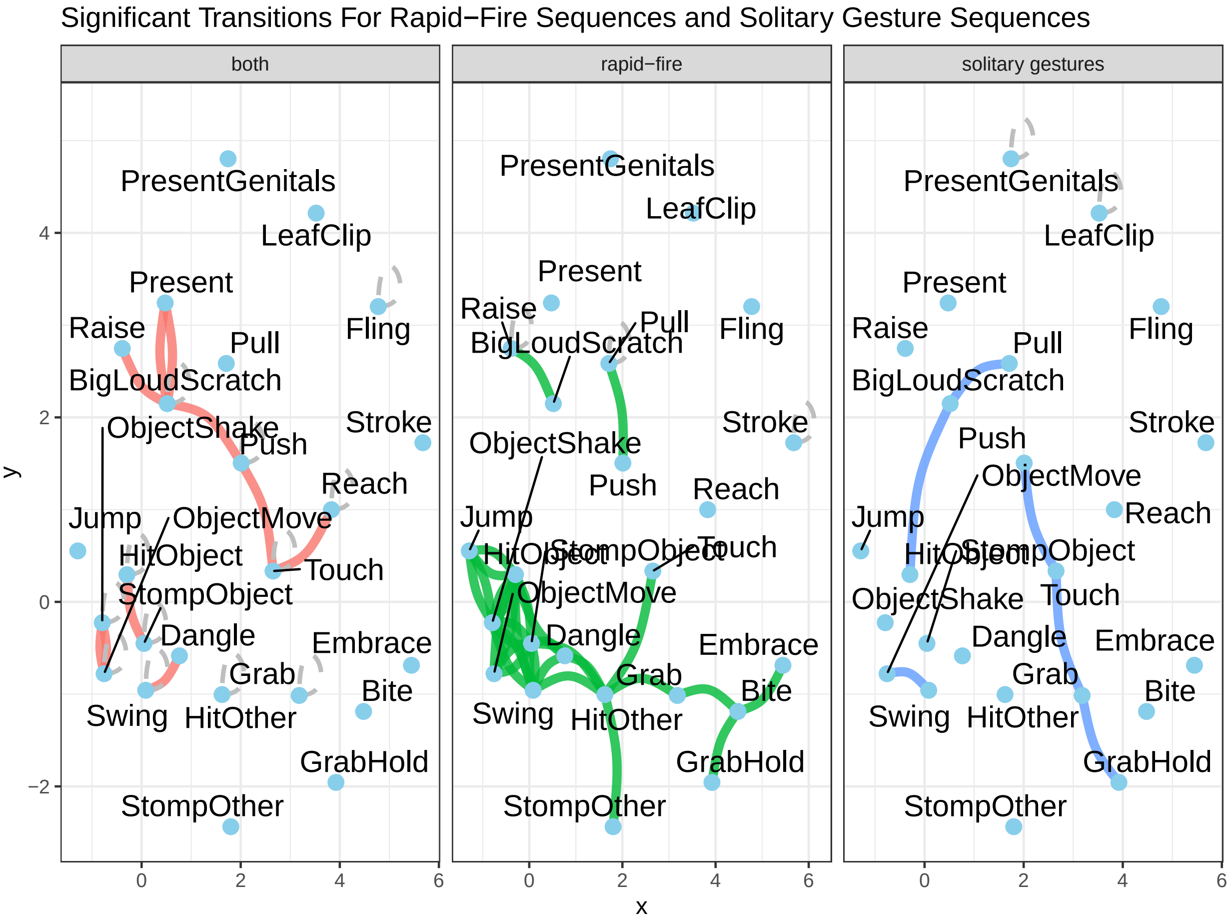
Concurrence Transition Network



7.3 Networks



7.3.1 Rapid response vs solitary gesture network



Rapid fire sequences are focused on object-related and contact gestures (stomping, hitting, biting, embracing) while the ones that definitely need response waiting are often those that cannot be physically done too quickly together or those that in a rapid-fire sequence would not be marked as distinct (without response waiting, there would be no way to tease apart Grab, GrabHold, Touch, and Push).

8 Significant 2-gram orders

Let's check if there are any combinations where the direction matters (conditional probability of B following A being more likely than expected by random distribution of elements within sequences). We shuffle elements within sequences while keeping sequence lengths the same. We do this for the 5sec full sequences for now.

8.1 Functions

8.2 Generate significance values

Make a list of the significant n-grams.

antecedent	consequent	count	conditional_probability	expected_within	improvement
Embrace	Bite	16	0.6400000	0.3416952	0.2983048
GrabHold	Bite	18	0.4186047	0.2301305	0.1884742
Grab	Bite	18	0.2535211	0.1246205	0.1289006
Jump	HitObject	7	0.2692308	0.1733109	0.0959198
Bite	HitOther	6	0.1714286	0.0947642	0.0766643
Raise	BigLoudScratch	23	0.3432836	0.2710566	0.0722270
Push	Touch	15	0.1648352	0.1112090	0.0536262
Swing	HitOther	11	0.0940171	0.0570022	0.0370149
Raise	StompObject	5	0.0746269	0.0376200	0.0370068
ObjectShake	StompObject	35	0.1346154	0.1025986	0.0320168
HitOther	StompOther	8	0.0601504	0.0347647	0.0253857
StompObject	HitObject	64	0.2735043	0.2507648	0.0227394
Push	Raise	6	0.0659341	0.0436033	0.0223308
HitObject	Jump	9	0.0381356	0.0165373	0.0215983
Touch	HitOther	5	0.0364964	0.0190859	0.0174104
StompObject	Dangle	10	0.0427350	0.0270353	0.0156998
Touch	GrabHold	7	0.0510949	0.0358942	0.0152007
ObjectShake	Swing	15	0.0576923	0.0429345	0.0147578
BigLoudScratch	Push	14	0.0522388	0.0375138	0.0147250
StompObject	HeadStand	5	0.0213675	0.0071485	0.0142190
BigLoudScratch	Pull	8	0.0298507	0.0204471	0.0094037

It mainly seems like physical contact (Bite, Pull, Push, Touch) usually follows rather than precedes other gestures.

9 Entropy

9.1 Functions

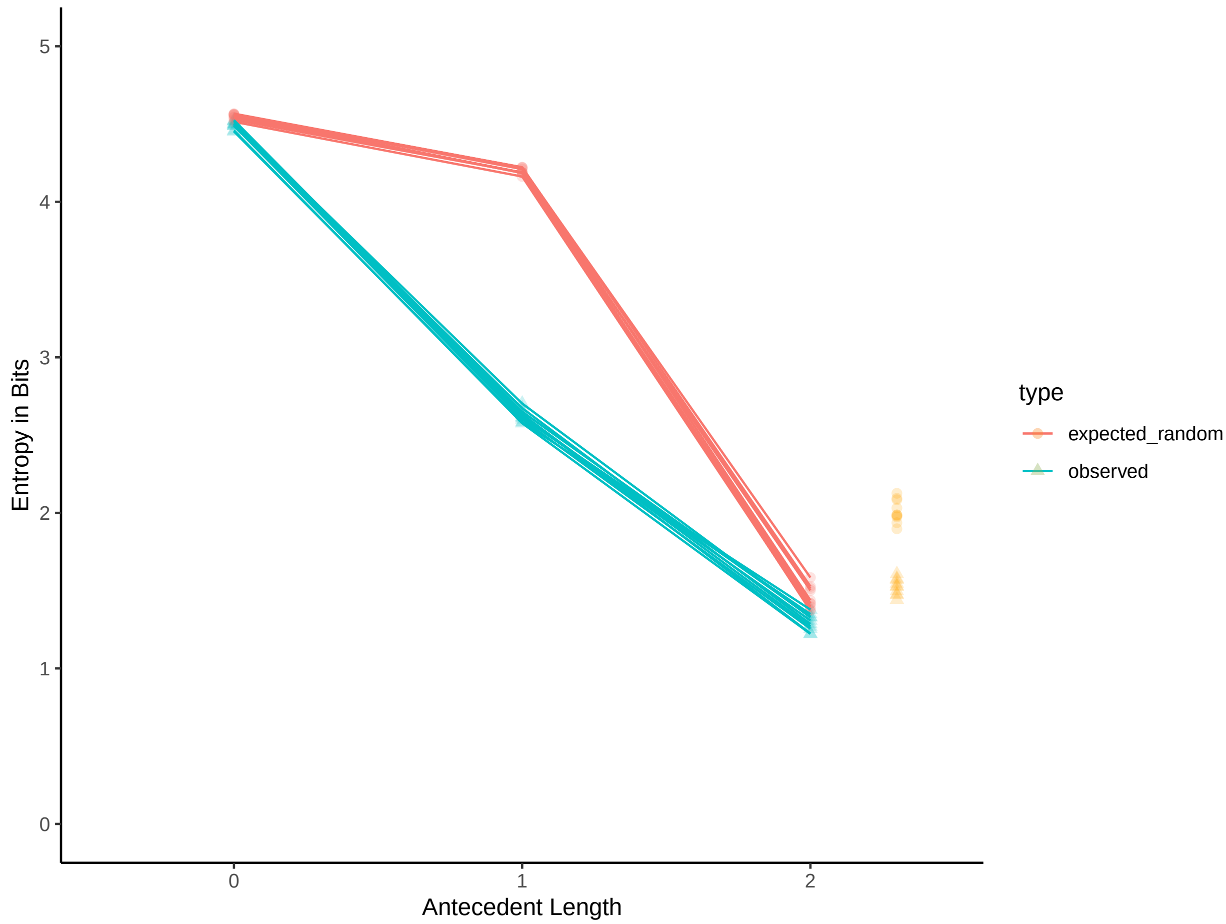
9.1.1 Calculate Entropy

This function calculates the entropy of a given sequence.

9.2 Entropies all datasets

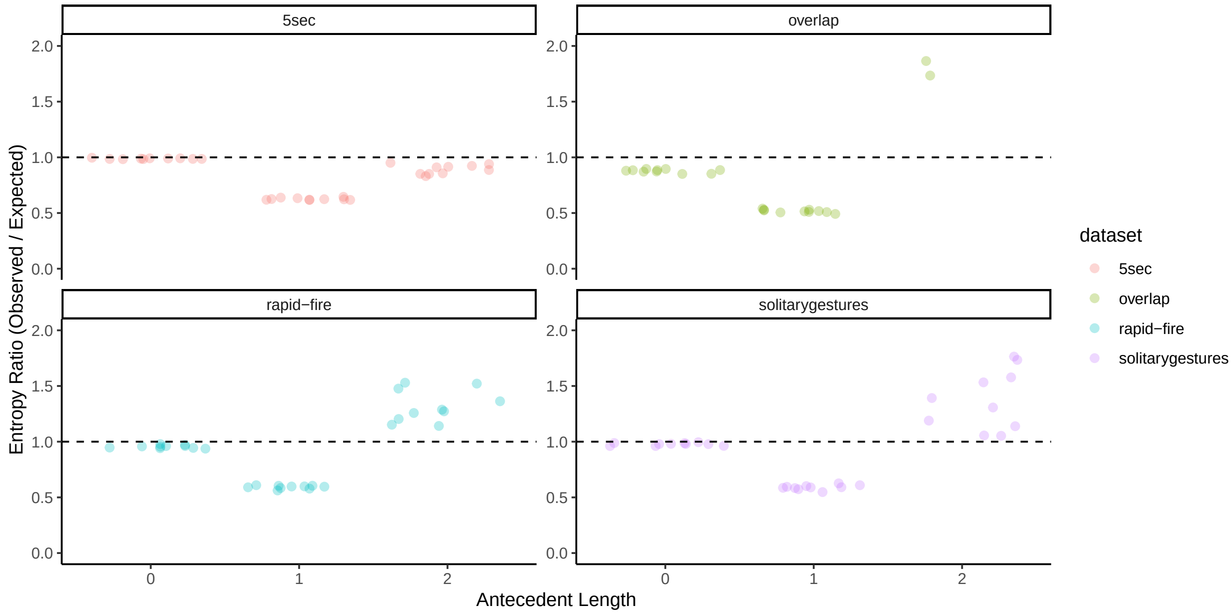
Calculate the entropies across all 5 datasets.

Let's plot this.



Doted lines are predicted for random, lower values mean 'less chaotic'. From the entropies, there is considerable improvement in predictability moving from no antecedent to one antecedent, but not from 1 antecedent to 2 antecedents. There seems a slight improvement of having 2 antecedent when the order is removed ('alphabetical'), indicating the order just adds noise.

Let's plot the ratio between expected and observed entropies. Anything closer to 1 or above means randomness, anything closer to 0 means more predictability.

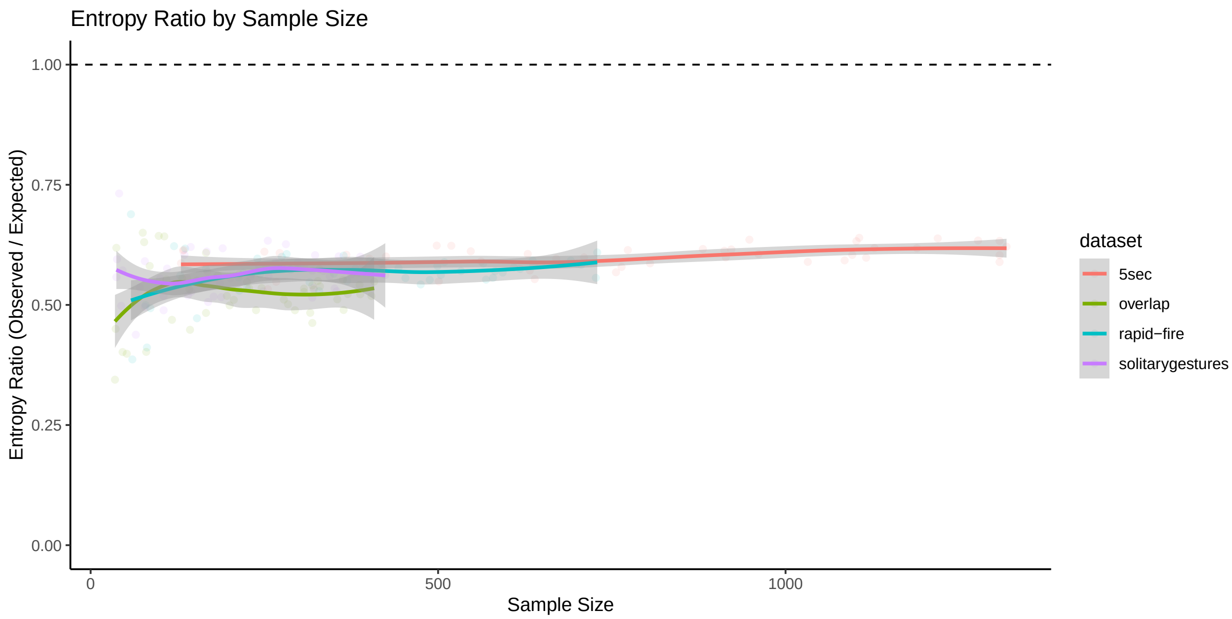


For level 0 and 1 (base probabilities and 1-element antecedents), the different sequence types are the same apart from the Overlap sequences, which are more predictable at Level 1 (which mirrors our results above, there are simply fewer options). For 2-antecedent transitions, the 5-second sequence definition adds the most predictability about what happens next; in 1-second sequences and overlap, there is no added information above random (most of them aren't even visible in this chart); the solitary gesture (which should be fairly similar anyways) add a bit of information, but on average less than the 5sec sequences.

9.2.1 Impact of sample size on entropies

The different datasets have different sample sizes. Let's check how the sample size impacts the entropy.

For the first level entropy, this looks like this: essentially, all datasets have sufficient data to accurately calculate the entropy inherent in the first order transitions, and they do not differ a lot (apart from overlap potentially having less entropy compared to predicted). The y-axis is the ratio between the observed and expected entropy values.



We make a table of the different expected and observed entropies for the full dataset for each:

dataset	level	order	entropy	expected_entropy	entropy_ratio
5sec	1	observed	2.435090	3.951228	0.6162869
overlap	1	observed	1.727917	3.296614	0.5241491
rapid-fire	1	observed	2.152752	3.678078	0.5852926
solitarygestures	1	observed	1.834860	3.252357	0.5641632

10 Prediction Models

10.1 Functions

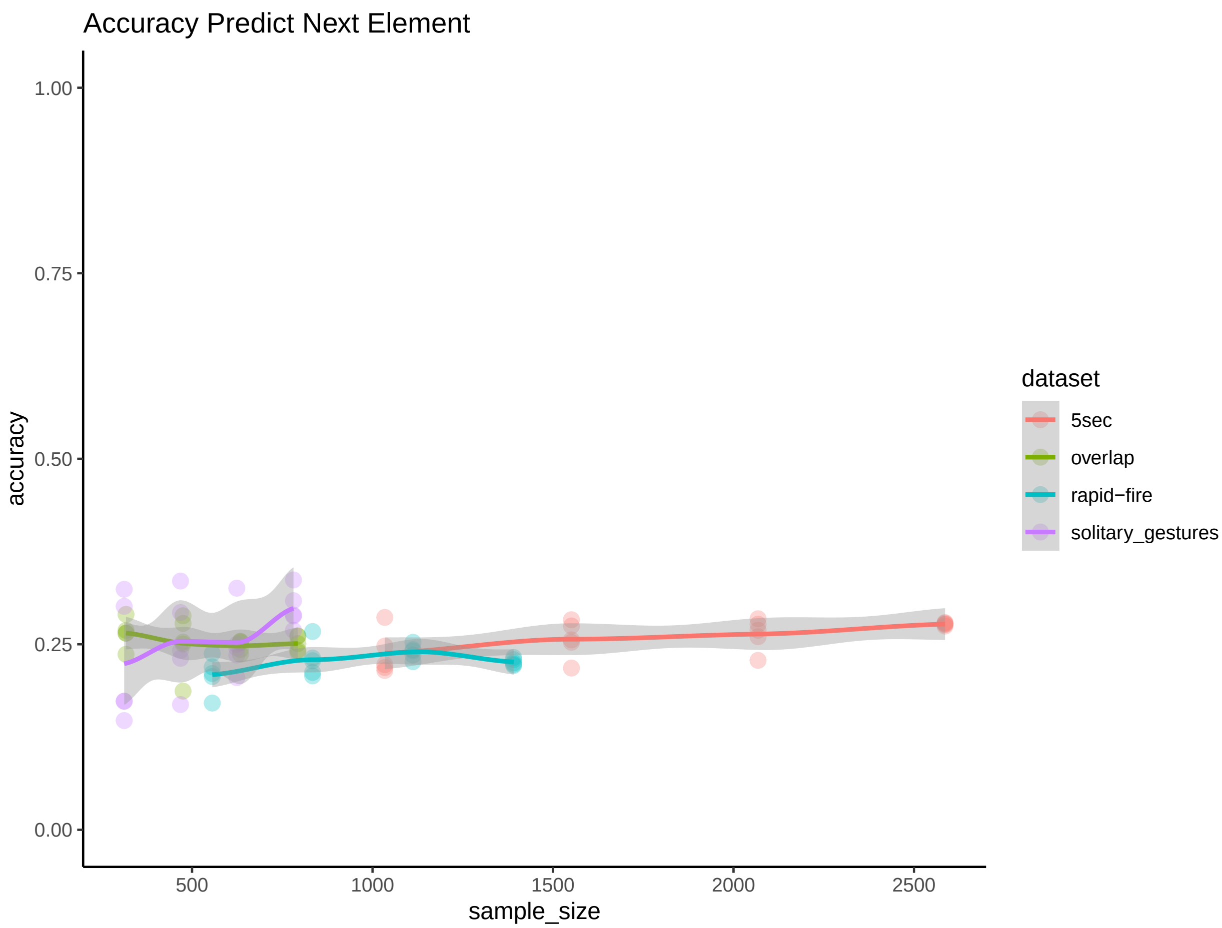
10.1.1 Comparison of predictability of different datasets

```
## [1] 1.0 0.4
```

```
## [1] 1.0 0.6
## [1] 1.0 0.8
## [1] 1 1
## [1] 1.0 0.4
## [1] 1.0 0.6
## [1] 1.0 0.8
## [1] 1 1
## [1] 1.0 0.4
## [1] 1.0 0.6
## [1] 1.0 0.8
## [1] 1 1
```

```
## [1] 1.0 0.4
## [1] 1.0 0.6
## [1] 1.0 0.8
## [1] 1 1
## [1] 1.0 0.4
## [1] 1.0 0.6
## [1] 1.0 0.8
## [1] 1 1
## [1] 2.0 0.4
## [1] 2.0 0.6
## [1] 2.0 0.8
## [1] 2 1
## [1] 2.0 0.4
## [1] 2.0 0.6
## [1] 2.0 0.8
## [1] 2 1
## [1] 2.0 0.4
## [1] 2.0 0.6
## [1] 2.0 0.8
## [1] 2 1
## [1] 2.0 0.4
## [1] 2.0 0.6
## [1] 2.0 0.8
## [1] 2 1
## [1] 2.0 0.4
## [1] 2.0 0.6
## [1] 2.0 0.8
## [1] 2 1
## [1] 3.0 0.4
## [1] 3.0 0.6
## [1] 3.0 0.8
## [1] 3 1
## [1] 3.0 0.4
## [1] 3.0 0.6
## [1] 3.0 0.8
## [1] 3 1
## [1] 3.0 0.4
## [1] 3.0 0.6
## [1] 3.0 0.8
## [1] 3 1
## [1] 3.0 0.4
## [1] 3.0 0.6
## [1] 3.0 0.8
## [1] 3 1
## [1] 3.0 0.4
```

```
## [1] 3.0 0.6
## [1] 3.0 0.8
## [1] 3 1
## [1] 4.0 0.4
## [1] 4.0 0.6
## [1] 4.0 0.8
## [1] 4 1
## [1] 4.0 0.4
## [1] 4.0 0.6
## [1] 4.0 0.8
## [1] 4 1
## [1] 4.0 0.4
## [1] 4.0 0.6
## [1] 4.0 0.8
## [1] 4 1
## [1] 4.0 0.4
## [1] 4.0 0.6
## [1] 4.0 0.8
## [1] 4 1
## [1] 4.0 0.4
## [1] 4.0 0.6
## [1] 4.0 0.8
## [1] 4 1
```



10.2 Higher-order predictions

10.2.1 Data preparation

Let's check how predictable transitions are on different levels. We use Naive Bayes classifier (which is agnostic to sequence information) and Random Forests to predict the next element based on the previous one. Originally, this also involved LSTM, but Long-Short Term Memory deep learning (which represents sequence information), but the overfitting was so extreme that it is hard to interpret the results. We look at 3-grams: AB predicting C. We check whether A alone (one gesture removed), B alone (previous gesture), AB together, or a alphabetisation of AB best predicts the next element.

10.2.2 Sequence Prediction