

1 TRex, a fast multi-animal tracking 2 system with markerless 3 identification, and 2D estimation of 4 posture and visual fields

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9

10 **Abstract** Automated visual tracking of animals is rapidly becoming an indispensable tool for
 11 the study of behavior. It offers a quantitative methodology by which organisms' sensing and
 12 decision-making can be studied in a wide range of ecological contexts. Despite this, existing
 13 solutions tend to be challenging to deploy in practice, especially when considering long and/or
 14 high-resolution video-streams. Here, we present TRex, a fast and easy-to-use solution for
 15 tracking a large number of individuals simultaneously [using background-subtraction](#) with
 16 real-time (60Hz) tracking performance for up to approximately 256 individuals and estimates 2D
 17 [visual-fields, outlines, and head/rear of bilateral animals](#), both in open and closed-loop contexts.
 18 Additionally, TRex offers highly-accurate, deep-learning-based visual identification of up to
 19 approximately 100 unmarked individuals, where it is between 2.5-46.7 times faster, and requires
 20 2-10 times less memory, than comparable software (with relative performance increasing for
 21 more organisms/longer videos) and provides interactive data-exploration within an intuitive,
 22 platform-independent graphical user-interface.

24 **Introduction**

25 Tracking multiple moving animals (and multiple objects, generally) is important in various fields of
 26 research such as behavioral studies, ecophysiology, biomechanics, and neuroscience ([Dell et al.](#)
 27 [\(2014\)](#)). Many tracking algorithms have been proposed in recent years ([Ohayon et al. \(2013\)](#), [Fuku-](#)
 28 [naga et al. \(2015\)](#), [Burgos-Artizzu et al. \(2012\)](#), [Rasch et al. \(2016\)](#)), often limited to/only tested with
 29 a particular organism ([Hewitt et al. \(2018\)](#), [Branson et al. \(2009\)](#)) or type of organism (e.g. pro-
 30 [tists](#), [Pennekamp et al. \(2015\)](#); fly larvae and worms, [Risse et al. \(2017\)](#)). Relatively few have been
 31 tested with a range of organisms and scenarios ([Pérez-Escudero et al. \(2014\)](#), [Sridhar et al. \(2019\)](#),
 32 [Rodríguez et al. \(2018\)](#)). Furthermore, many existing tools only have a specialized set of features,
 33 struggle with very long or high-resolution ($\geq 4K$) videos, or simply take too long to yield results. Existing
 34 fast algorithms are often severely limited with respect to the number of individuals that can be
 35 tracked simultaneously; for example xyTracker ([Rasch et al. \(2016\)](#)) allows for real-time tracking at
 36 40Hz while accurately maintaining identities, and thus is suitable for closed-loop experimentation
 37 (experiments where stimulus presentation can depend on the real-time behaviors of the individ-
 38 uals, e.g. [Bath et al. \(2014\)](#), [Brembs and Heisenberg \(2000\)](#), [Bianco and Engert \(2015\)](#)), but has a
 39 limit of being able to track only 5 individuals simultaneously. ToxTrac ([Rodríguez et al. \(2018\)](#)), a

40 software comparable to xyTracker in its set of features, is limited to 20 individuals and relatively
 41 low frame-rates ($\leq 25\text{fps}$). Others, while implementing a wide range of features and offering high-
 42 performance tracking, are costly and thus limited in access (**Noldus et al. (2001)**). Perhaps with
 43 the exception of proprietary software, one major problem at present is the severe fragmentation
 44 of features across the various software solutions. For example, experimentalists must typically
 45 construct work-flows from many individual tools: One tool might be responsible for estimating
 46 the animal's positions, another for estimating their posture, another one for reconstructing visual
 47 fields (which in turn probably also estimates animal posture, but does not export it in any way)
 48 and one for keeping identities – correcting results of other tools post-hoc. It can take a very long
 49 time to make them all work effectively together, adding what is often considerable overhead to
 50 behavioral studies.

51 TRex, the software released with this publication (available at trex.run under an Open-Source
 52 license), has been designed to address these problems, and thus to provide a powerful, fast and
 53 easy to use tool that will be of use in a wide range of behavioral studies. It allows users to track
 54 moving objects/animals, as long as there is a way to separate them from the background (e.g.
 55 static backgrounds, custom masks, as discussed below). In addition to the positions of individuals,
 56 our software provides other per-individual metrics such as body shape and, if applicable, head-
 57 /tail-position. This is achieved using a basic posture analysis, which works out of the box for most
 58 organisms, and, if required, can be easily adapted for others. Posture information, which includes
 59 the body center-line, can be useful for detecting e.g. courtship displays and other behaviors that
 60 might not otherwise be obvious from mere positional data. Additionally, with the visual sense
 61 often being one of the most important modalities to consider in behavioral research, we include
 62 the capability for users to obtain a computational reconstruction of the visual fields of all individuals
 63 (**Strandburg-Peshkin et al. 2013, Rosenthal et al. 2015**). This not only reveals which individuals are
 64 visible from an individual's point-of-view, as well as the distance to them, but also which parts of
 65 others' bodies are visible.

66 Included in the software package is a task-specific tool, **TGrabs**, that is employed to pre-process
 67 existing video files and which allows users to record directly from cameras capable of live-streaming
 68 to a computer (with extensible support from generic webcams to high-end machine vision cam-
 69 eras). It supports most of the above-mentioned tracking features (positions, posture, visual field)
 70 and provides access to results immediately while continuing to record/process. This not only saves
 71 time, since tracking results are available immediately after the trial, but makes closed-loop support
 72 possible for large groups of individuals (≤ 128 individuals). TRex and TGrabs are written in C++ but,
 73 as part of our closed-loop support, we are providing a Python-based general scripting interface
 74 which can be fully customized by the user without the need to recompile or relaunch. This inter-
 75 face allows for compatibility with external programs (e.g. for closed-loop stimulus-presentation)
 76 and other custom extensions.

77 The fast tracking described above employs information about the kinematics of each organ-
 78 ism in order to try to maintain their identities. This is very fast and useful in many scenarios, e.g.
 79 where general assessments about group properties (group centroid, alignment of individuals, den-
 80 sity, etc.) are to be made. However, when making conclusions about *individuals* instead, main-
 81 taining identities perfectly throughout the video is a critical requirement. Every tracking method
 82 inevitably makes mistakes, which, for small groups of two or three individuals or short videos, can
 83 be corrected manually – at the expense of spending much more time on analysis, which rapidly
 84 becomes prohibitive as the number of individuals to be tracked increases. To make matters worse,
 85 when multiple individuals stay out of view of the camera for too long (such as if individuals move
 86 out of frame, under a shelter, or occlude one another) there is no way to know who is whom
 87 once they re-emerge. With no baseline truth available (e.g. using physical tags as in **Alarcón-Nieto**
 88 **et al. (2018), Nagy et al. (2013)**; or marker-less methods as in **Pérez-Escudero et al. (2014), Romero-**
 89 **Ferrero et al. (2019), Rasch et al. (2016)**), these mistakes can not be corrected and accumulate over
 90 time, until eventually all identities are fully shuffled. To solve this problem (and without the need

91 to mark, or add physical tags to individuals), TRex can, at the cost of spending more time on analy-
 92 sis (and thus not during live-tracking), automatically learn the identity of up to approximately 100
 93 unmarked individuals based on their visual appearance. This machine-learning based approach,
 94 herein termed *visual identification*, provides an independent source of information on the identity
 95 of individuals, which is used to detect and correct potential tracking mistakes without the need for
 96 human supervision.

97 In this paper, we evaluate the most important functions of our software in terms of speed
 98 and reliability using a wide range of experimental systems, including termites, fruit flies, locusts
 99 and multiple species of schooling fish (although we stress that our software is not limited to such
 100 species).

101 Specifically regarding the visual identification of unmarked individuals in groups, `idtracker.ai`
 102 is currently state-of-the-art, yielding high-accuracy (>99% in most cases) in maintaining consistent
 103 identity assignments across entire videos (*Romero-Ferrero et al. (2019)*). Similarly to TRex, this is
 104 achieved by training an artificial neural network to visually differentiate between individuals, and
 105 using identity predictions from this network to avoid/correct tracking mistakes. Both approaches
 106 work without human supervision, and are limited to approximately 100 individuals. Given that
 107 `idtracker.ai` is the only currently available tool with visual identification for such large groups of
 108 individuals, and also because of the quality of results, we will use it as a benchmark for our visual
 109 identification system. Results will be compared in terms of both accuracy and computation speed,
 110 showing TRex' ability to achieve the same high level of accuracy but typically at far higher speeds,
 111 and with a much reduced memory requirement.

112 TRex is platform-independent and runs on all major operating systems (Linux, Windows, macOS)
 113 and offers complete batch processing support, allowing users to efficiently process entire sets
 114 of videos without requiring human intervention. All parameters can be accessed either through
 115 settings files, from within the graphical user interface (or *GUI*), or using the command-line. The
 116 user interface supports off-site access using a built-in web-server (although it is recommended
 117 to only use this from within a secure VPN environment). Available parameters are explained in
 118 the documentation directly as part of the GUI and on an external website (see below). Results
 119 can be exported to independent data-containers (`NPZ`, or `CSV` for plain-text type data) for further
 120 analyses in software of the user's choosing. We will not go into detail regarding the many GUI
 121 functions since albeit being of great utility to the researcher, they are only the means to easily
 122 apply the features presented herein. Some examples will be given in the main text and appendix,
 123 but a comprehensive collection of all of them, as well as detailed documentation, is available in the
 124 up-to-date online-documentation which can be found at trex.run/docs.

125 Results

126 Our software package consists of two task-specific tools, `TGrabs` and `TRex`, with different special-
 127izations. `TGrabs` is primarily designed to connect to cameras and to be very fast. It employs the
 128 same program code as `TRex` to achieve real-time online tracking, such as could be employed for
 129 closed-loop experiments (the user can launch `TGrabs` from the opening dialog of `TRex`). However,
 130 its focus on speed comes at the cost of not having access to the rich graphical user interface or
 131 more sophisticated (and thus slower) processing steps, such as deep-learning based identification,
 132 that `TRex` provides. `TRex` focusses on the more time-consuming tasks, as well as visual data explo-
 133 ration, re-tracking existing results – but sometimes it simply functions as an easier-to-use graphical
 134 interface for tracking and adjusting parameters. Together they provide a wide range of capabili-
 135 ties to the user and are often used in sequence as part of the same work-flow. Typically, such a
 136 sequence can be summarized in four stages (see also *Figure 2* for a flow diagram):

137 1. **Segmentation** in `TGrabs`. When recording a video or converting a previously recorded file
 138 (e.g. MP4, .AVI, etc.), it is segmented into background and foreground-objects (`blobs`), the
 139 latter typically being the entities to be tracked. Results are saved to a custom, non-proprietary

- 140 video format (PV) (**Figure 1a**).
 141 2. **Tracking** the video, either directly in TGrabs, or in TRex after pre-processing, with access to
 142 customizable visualizations and the ability to change tracking parameters on-the-fly. Here, we
 143 will describe two types of data available within TRex, 2D posture- and visual-field estimation,
 144 as well as real-time applications of such data (**Figure 1b**).
 145 3. **Automatic identity correction** (**Figure 1c**), a way of utilizing the power of a trained neural
 146 network to perform visual identification of individuals, is available in TRex only. This step
 147 may not be necessary in many cases, but it is the only way to guarantee consistent identities
 148 throughout the video. It is also the most processing-heavy (and thus usually the most time-
 149 consuming) step, as well as the only one involving machine learning. All previously collected
 150 posture- and other tracking-related data are utilized in this step, placing it late in a typical
 151 workflow.
 152 4. Data visualization is a critical component of any research project, especially for unfamiliar
 153 datasets, but manually crafting one for every new experiment can be very time-consuming.
 154 Thus, TRex offers a universal, highly customizable, way to make all collected data available
 155 for interactive **exploration** (**Figure 1d**) – allowing users to change many display options and
 156 recording video clips for external playback. Tracking parameters can be adjusted on the fly
 157 (many with visual feedback) – important e.g. when preparing a closed-loop feedback with a
 158 new species or setup.

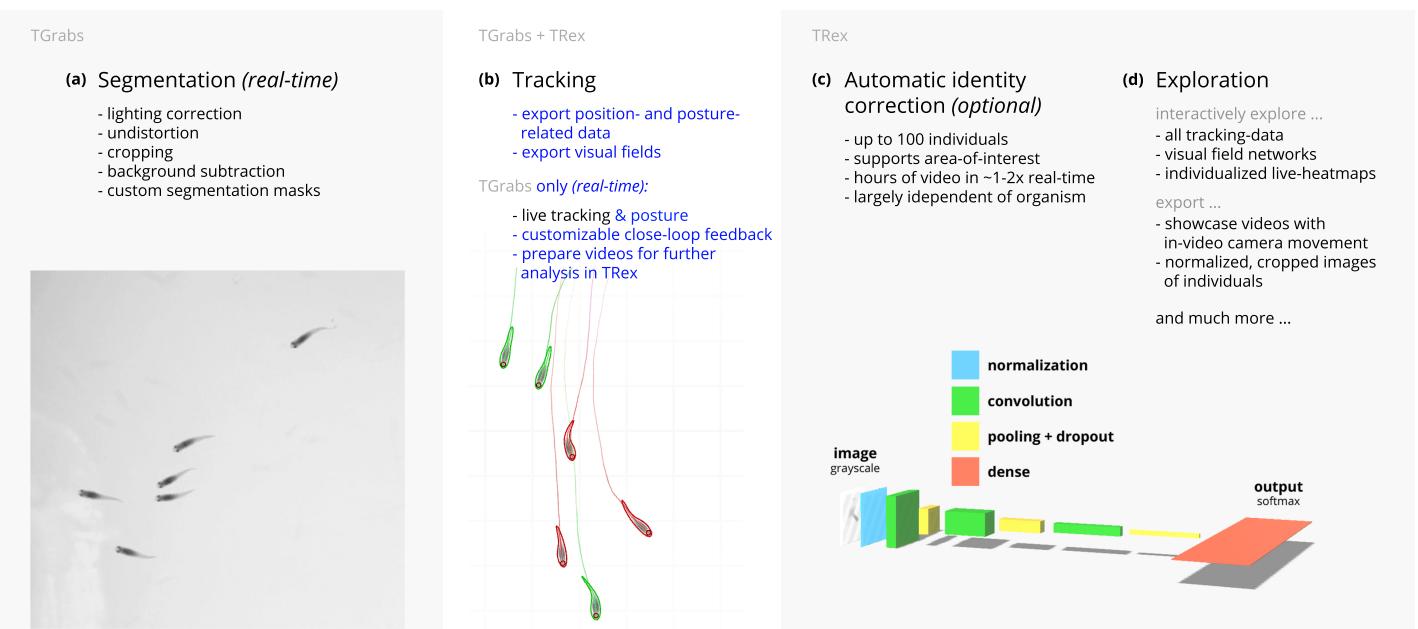


Figure 1. Videos are typically processed in four main stages, illustrated here each with a list of prominent features. Some of them are accessible from both TRex and TGrabs, while others are software specific (as shown at the very top). (a) The video is either recorded directly with our software (TGrabs), or converted from a pre-recorded video file. Live-tracking enables users to perform closed-loop experiments, for which a virtual testing environment is provided. (b) Videos can be tracked and parameters adjusted with visual feedback. Various exploration and data presentation features are provided and customized data streams can be exported for use in external software. (c) After successful tracking, automatic visual identification can, optionally, be used to refine results. An artificial neural network is trained to recognize individuals, helping to automatically correct potential tracking mistakes. In the last stage, many graphical tools are available to users of TRex, a selection of which is listed in (d).

Figure 1-video 1. This video shows an overview of the typical chronology of operations when using our software. Starting with the raw video, segmentation using TGrabs (**Figure 1a**) is the first and only step that is not optional. Tracking (**Figure 1b**) and posture estimation (both also available for live-tracking in TGrabs) are usually performed in that order, but can be partly parallelized (e.g. performing posture estimation in parallel for all individuals). Visual identification (**Figure 1c**) is only available in TRex due to relatively long processing times. All clips from this composite video have been recorded directly in TRex. <https://youtu.be/g9EOi7FZHM0>

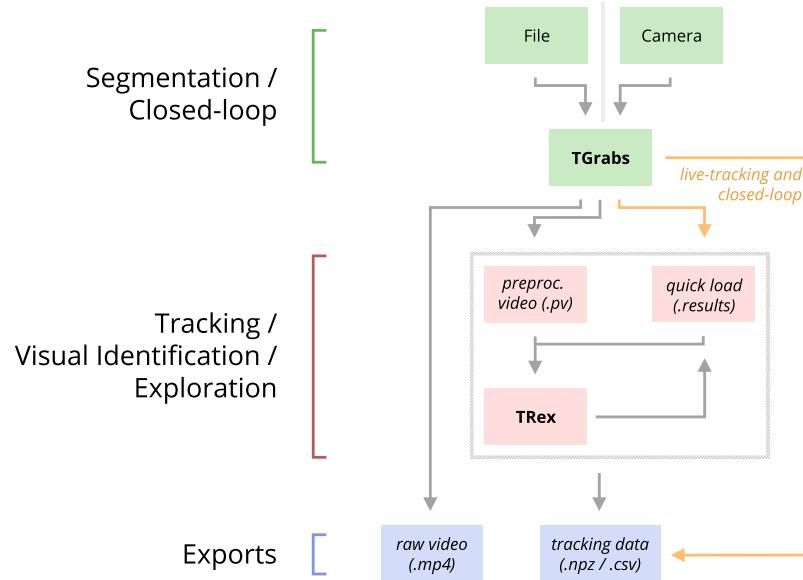


Figure 2. An overview of the interconnection between TRex, TGrabs and their data in- and output formats, with titles on the left corresponding to the stages in **Figure 1**. Starting at the top of the figure, video is either streamed to TGrabs from a file or directly from a compatible camera. At this stage, preprocessed data are saved to a `.pv` file which can be read by TRex later on. Thanks to its integration with parts of the TRex code, TGrabs can also perform online tracking for limited numbers of individuals, and save results to a `.results` file (that can be opened by TRex) along with individual tracking data saved to numpy data-containers (`.npz`) or standard CSV files, which can be used for analysis in third-party applications. If required, videos recorded directly using TGrabs can also be streamed to a `.mp4` video file which can be viewed in commonly available video players like VLC.

159 Below we assess the performance [of our software](#) regarding three properties that are most
160 important when using it (or in fact any tracking software) in practice: (i) The time it takes to perform
161 tracking (ii) the time it takes to perform automatic identity correction and (iii) the peak memory
162 consumption when correcting identities (since this is where memory consumption is maximal), as
163 well as (iv) the accuracy of the produced trajectories after visual identification.

164 While accuracy is an important metric and specific to identification tasks, time and memory are
165 typically of considerable practical importance for all tasks. For example, tracking-speed may be
166 the difference between only being able to run a few trials or producing more reliable results with
167 a much larger number of trials. In addition, tracking speed can make a major difference as the
168 number of individuals increases. Furthermore, memory constraints can be extremely prohibitive
169 making tracking over long video sequences and/or for a large number of individuals extremely
170 time-consuming, or impossible, for the user.

171 In all of our tests we used a relatively modest computer system, which could be described as a
172 mid-range consumer or gaming PC:

- 173 • Intel Core i9-7900X CPU
- 174 • NVIDIA Geforce 1080 Ti
- 175 • 64GB RAM
- 176 • NVMe PCIe x4 hard-drive
- 177 • Debian bullseye (debian.org)

178 As can be seen in the following sections (memory consumption, processing speeds, etc.) using
179 a high-end system is not necessary to run TRex and, anecdotally, we did not observe noticeable
180 improvements when using a solid state drive versus a normal hard drive. A video card (presently
181 an NVIDIA card due to the requirements of TensorFlow) is recommended for tasks involving visual
182 identification as such computations will take much longer without it – however, it is not required.
183 We decided to employ this system due to having a relatively cheap, compatible graphics card, as

ID	species	common	# ind.	fps (Hz)	duration	size (px ²)
0	<i>Leucaspis delineatus</i>	sunbleak	1024	40	8min20s	3866 x 4048
1	<i>Leucaspis delineatus</i>	sunbleak	512	50	6min40s	3866 x 4140
2	<i>Leucaspis delineatus</i>	sunbleak	512	60	5min59s	3866 x 4048
3	<i>Leucaspis delineatus</i>	sunbleak	256	50	6min40s	3866 x 4140
4	<i>Leucaspis delineatus</i>	sunbleak	256	60	5min59s	3866 x 4048
5	<i>Leucaspis delineatus</i>	sunbleak	128	60	6min	3866 x 4048
6	<i>Leucaspis delineatus</i>	sunbleak	128	60	5min59s	3866 x 4048
7	<i>Danio rerio</i>	zebrafish	100	32	1min	3584 x 3500
8	<i>Drosophila melanogaster</i>	fruit-fly	59	51	10min	2306 x 2306
9	<i>Schistocerca gregaria</i>	locust	15	25	1h0min	1880 x 1881
10	<i>Constrictotermes cyphergaster</i>	termite	10	100	10min5s	1920 x 1080
11	<i>Danio rerio</i>	zebrafish	10	32	10min10s	3712 x 3712
12	<i>Danio rerio</i>	zebrafish	10	32	10min3s	3712 x 3712
13	<i>Danio rerio</i>	zebrafish	10	32	10min3s	3712 x 3712
14	<i>Poecilia reticulata</i>	guppy	8	30	3h15min22s	3008 x 3008
15	<i>Poecilia reticulata</i>	guppy	8	25	1h12min	3008 x 3008
16	<i>Poecilia reticulata</i>	guppy	8	35	3h18min13s	3008 x 3008
17	<i>Poecilia reticulata</i>	guppy	1	140	1h9min32s	1312 x 1312

Table 1. A list of the videos used in this paper as part of the evaluation of TRex, along with the species of animals in the videos and their common names, as well as other video-specific properties. Videos are given an incremental ID, to make references more efficient in the following text, which are sorted by the number of individuals in the video. Individual quantities are given accurately, except for the videos with more than 100 where the exact number may be slightly more or less. These videos have been analysed using TRex' dynamic analysis mode that supports unknown quantities of animals.

Table 1-source data 1. Videos 7 and 8, as well as 13-11, are available as part of the original idtracker paper ([Pérez-Escudero et al. \(2014\)](#)). Many of the videos are part of yet unpublished data: Guppy videos have been recorded by A. Albi, videos with sunbleak (*Leucaspis delineatus*) have been recorded by D. Bath. The termite video has been kindly provided by H. Hugo and the locust video by F. Oberhauser. Due to the size of some of these videos (>150GB per video), they have to be made available upon specific request. Raw versions of these videos (some trimmed), as well as full preprocessed versions, are available as part of the dataset published alongside this paper [Walter et al. \(2020\)](#).

well as to ensure that we have an easy way to produce direct comparisons with [idtracker.ai](#) – which according to their website requires large amounts of RAM (32-128GB, [idtrackerai online documentation](#)) and a fast solid-state drive.

Table 1 shows the entire set of videos used in this paper, which have been obtained from multiple sources (credited under the table) and span a wide range of different organisms, demonstrating TRex' ability to track anything as long as it moves occasionally. Videos involving a large number (>100) of individuals are all the same species of fish since these were the only organisms we had available in such quantities. However, this is not to say that only fish could be tracked efficiently in these quantities. We used the full dataset with up to 1024 individuals in one video (video 0) to evaluate raw tracking speed without visual identification and identity corrections (next sub-section). However, since such numbers of individuals exceed the capacity of the neural network used for automatic identity corrections (compare also [Romero-Ferrero et al. \(2019\)](#) who used a similar network), we only used a subset of these videos (videos 7 through 16) to look specifically into the quality of our visual identification in terms of keeping identities and its memory consumption.

198 **Tracking: Speed and Accuracy**

199 In evaluating the Tracking portion of TRex, the main focus lies with processing speed, while accuracy
 200 in terms of keeping identities is of secondary importance. Tracking is required in all other
 201 parts of the software, making it an attractive target for extensive optimization. Especially with re-
 202 gards to closed-loop, and live-tracking situations, there may be no room even to lose a millisecond
 203 between frames and thus risk dropping frames. We therefore designed TRex to support the simulta-
 204 neous tracking of many (≥ 256) individuals *quickly* and achieve reasonable *accuracy* for up to 100
 205 individuals – which are the two suppositions we will investigate in the following.

206 Trials were run without posture/visual-field estimation enabled, where tracking generally, and
 207 consistently, reaches speeds faster than real-time (processing times of 1.5-40% of the video du-
 208 ration, 25-100Hz) even for a relatively large number of individuals (77-94.77% for up to 256 indi-
 209 viduals, see *Appendix 4 Table A1*). Videos with more individuals (>500) were still tracked within
 210 reasonable time of 235% to 358% of the video duration. As would be expected from these re-
 211 sults, we found that combining tracking and recording in a single step generally leads to higher
 212 processing speeds. The only situation where this was not the case was a video with 1024 individu-
 213 als, which suggests that live-tracking (in TGrabs) handles cases with many individuals slightly worse
 214 than offline tracking (in TRex). Otherwise, 5% to 35% shorter total processing times were measured
 215 (14.55% on average, see *Appendix 4 Table A4*), compared to running TGrabs separately and then
 216 tracking in TRex. These percentage differences, in most cases, reflect the ratio between the video
 217 duration and the time it takes to track it, suggesting that most time is spent – by far – on the conver-
 218 sion of videos. This additional cost can be avoided in practice when using TGrabs to record videos,
 219 by directly writing to a custom format recognized by TRex, and/or using its live-tracking ability to
 220 export tracking data immediately after the recording is stopped.

221 We also investigated trials that were run with posture estimation *enabled* and we found that real-
 222 time speed could be achieved for videos with ≤ 128 individuals (see column "tracking" in *Appendix 4*
 223 *Table A4*). Tracking speed, when posture estimation is enabled, depends more strongly on the size
 224 of individuals in the image.

225 Generally, tracking software becomes slower as the number of individuals to be tracked in-
 226 creases, as a result of an exponentially growing number of combinations to consider during match-
 227 ing. *TRex uses a novel tree-based algorithm by default (see Tracking), but circumvents problematic*
 228 *situations by falling back on using the Hungarian method (also known as the Kuhn-Munkres algo-*
 229 *rithm, Kuhn (1955))* when necessary. Comparing our mixed approach (see Tracking) to purely using
 230 the Hungarian method shows that, while both perform similarly for few individuals, the Hungarian
 231 method is easily outperformed by our algorithm for larger groups of individuals (as can be seen
 232 in *Appendix 4 Figure A3*). This might be due to custom optimizations regarding local cliques of
 233 individuals, whereby we ignore objects that are too far away, and also as a result of our optimized
 234 pre-sorting. The Hungarian method has the advantage of not leading to combinatorical explosions
 235 in some situations – and thus has a lower *maximum* complexity while proving to be less optimal in
 236 the *average* case. For further details, see the appendix: Matching an object to an object in the next
 237 frame.

238 In addition to speed, we also tested the accuracy of our tracking method, with regards to
 239 the consistency of identity assignments, comparing its results to the manually reviewed data (the
 240 methodology of which is described in the next section). In order to avoid counting follow-up errors
 241 as "new" errors, we divided each trajectory in the uncorrected data into "uninterrupted" segments
 242 of frames, instead of simply comparing whole trajectories. A segment is interrupted when an in-
 243 dividual is lost (for any of the reasons given in Preparing Tracking-Data) and starts again when it
 244 is reassigned to another object later on. We term these (re-)assignments *decisions* here. Each seg-
 245 ment of every individual can be uniquely assigned to a similar/identical segment in the baseline
 246 data and its identity. Following one trajectory in the uncorrected data, we can detect these wrong
 247 decisions by checking whether the baseline identity associated with one segment of that trajectory

video	# ind.	N TRex	% similar individuals	ϕ final uniqueness
7	100	5	99.8346 ± 0.5265	0.9758 ± 0.0018
8	59	5	98.6885 ± 2.1145	0.9356 ± 0.0358
13	10	5	99.9902 ± 0.3737	0.9812 ± 0.0013
11	10	5	99.9212 ± 1.1208	0.9461 ± 0.0039
12	10	5	99.9546 ± 0.8573	0.9698 ± 0.0024
14	8	5	98.8359 ± 5.8136	0.9192 ± 0.0077
15	8	5	99.2246 ± 4.4486	0.9576 ± 0.0023
16	8	5	99.7704 ± 2.1994	0.9481 ± 0.0025

Table 2. Evaluating comparability of the automatic visual identification between `idtracker.ai` and `TRex`. Columns show various video properties, as well as the associated uniqueness score (see **Box 1**) and a similarity metric. Similarity (% similar individuals) is calculated based on comparing the positions for each identity exported by both tools, choosing the closest matches overall and counting the ones that are differently assigned per frame. An individual is classified as "wrong" in that frame, if the euclidean distance between the matched solutions from `idtracker.ai` and `TRex` exceeds 1% of the video width. The column "% similar individuals" shows percentage values, where a value of 99% would indicate that, on average, 1% of the individuals are assigned differently. To demonstrate how uniqueness corresponds to the quality of results, the last column shows the average uniqueness achieved across trials.

Table 2-source data 1. This file contains all X and Y positions for each trial and each software combined into one very large table. This data is also available in different formats in [Walter et al. \(2020\)](#).

Table 2-source data 2. Assignments between identities from multiple solutions, as calculated by a bipartite-graph matching algorithm. For each permutation of trials from `TRex` and `idtracker.ai` for the same video, the algorithm sought to match the trajectories of the same physical individuals in both trials with each other by finding the ones with the smallest mean euclidean distance per frame between them. Available at <http://dx.doi.org/10.17617/3.4y>, as `T2_source_data.zip`.

248 changes in the next. We found that roughly 80% of such decisions made by the tree-based matching
 249 were correct, even with relatively high numbers of individuals (100). For trajectories where
 250 no manually reviewed data were available, we used automatically corrected trajectories as a base
 251 for our comparison – we evaluate the accuracy of these automatically corrected trajectories in the
 252 following section. Even though we did not investigate accuracy in situations with more than 100
 253 individuals, we suspect similar results since the property with the strongest influence on tracking
 254 accuracy – individual density – is limited physically and most of the investigated species school
 255 tightly in either case.

256 Visual Identification: Accuracy

257 Since the goal of using visual identification is to generate consistent identity assignments, we eval-
 258 uated the accuracy of our method in this regard. As a benchmark, we compare it to manually
 259 reviewed datasets as well as results from `idtracker.ai` for the same set of videos (where possi-
 260 ble). In order to validate trajectories exported by either software, we manually reviewed multiple
 261 videos with the help from a tool within `TRex` that allows to view each crossing and correct possi-
 262 ble mistakes in-place. Assignments were deemed incorrect, and subsequently corrected by the
 263 reviewer, if the centroid of a given individual was not contained within the object it was assigned
 264 to (e.g. the individual was not part of the correct object). Double assignments per object are im-
 265 possible due to the nature of the tracking method. Individuals were also forcibly assigned to the
 266 correct objects in case they were visible but not detected by the tracking algorithm. After manual
 267 corrections had been applied, "clean" trajectories were exported – providing a per-frame baseline
 268 truth for the respective videos. A complete table of reviewed videos, and the percentage of re-
 269 viewed frames per video, can be found in **Table 3**. For longer videos (>1h) we relied entirely on
 270 a comparison between results from `idtracker.ai` and `TRex`. Their paper ([Romero-Ferrero et al.](#)

video metrics		review stats		% correct	
video	# ind.	reviewed (%)	of that interpolated (%)	TRex	idtracker.ai
7	100	100.0	0.23	99.97 ± 0.013	98.95 ± 0.146
8	59	100.0	0.15	99.68 ± 0.533	99.94 ± 0.0
9	15	22.2	8.44	95.12 ± 6.077	N/A
10	10	100.0	1.21	99.7 ± 0.088	N/A
13	10	100.0	0.27	99.98 ± 0.0	99.96 ± 0.0
12	10	100.0	0.59	99.94 ± 0.006	99.63 ± 0.0
11	10	100.0	0.5	99.89 ± 0.009	99.34 ± 0.002

Table 3. Results of the human validation for a subset of videos. Validation was performed by going through all problematic situations (e.g. individuals lost) and correcting mistakes manually, creating a fully corrected dataset for the given videos. This dataset may still have missing frames for some individuals, if they could not be detected in certain frames (as indicated by "of that interpolated"). This was usually a very low percentage of all frames, except for video 9, where individuals tended to rest on top of each other – and were thus not tracked – for extended periods of time. This baseline dataset was compared to all other results obtained using the automatic visual identification by TRex ($N = 5$) and idtracker.ai ($N = 3$) to estimate correctness. We were not able to track videos 9 and 10 with idtracker.ai, which is why correctness values are not available.

Table 3-source data 1. A table of positions for each individual of each manually approved and corrected trial.

(2019)) suggests a very high accuracy of over 99.9% correctly identified individual images for most videos, which should suffice for most relevant applications and provide a good baseline truth. As long as both tools produce sufficiently similar trajectories, we therefore know they have found the correct solution.

A direct comparison between TRex and idtracker.ai was not possible for videos 9 and 10, where idtracker.ai frequently exceeded hardware memory-limits and caused the application to be terminated, or did not produce usable results within multiple days of run-time. However, we were able to successfully analyse these videos with TRex and evaluate its performance by comparing to manually reviewed trajectories (see below in Visual Identification: Accuracy). Due to the stochastic nature of machine learning, and thus the inherent possibility of obtaining different results in each run, as well as other potential factors influencing processing time and memory consumption, both TRex and idtracker.ai have been executed repeatedly (5x TRex, 3x idtracker.ai).

The trajectories exported by both idtracker.ai and TRex were very similar throughout (see Table 2). While occasional disagreements happened, similarity scores were higher than 98% in all and higher than 99% in most cases (i.e. less than 1% of individuals have been differently assigned in each frame on average). Most difficulties that did occur were, after manual review, attributable to situations where multiple individuals cross over excessively within a short time-span. In each case that has been manually reviewed, identities switched back to the correct individuals – even after temporary disagreement. We found that both solutions occasionally experienced these same problems, which often occur when individuals repeatedly come in and out of view in quick succession (e.g. overlapping with other individuals). Disagreements were expected for videos with many such situations due to the way both algorithms deal differently with them: idtracker.ai assigns identities only based on the network output. In many cases, individuals continue to partly overlap even while already being tracked, which results in visual artifacts and can lead to unstable predictions by the network and causing idtracker.ai's approach to fail. Comparing results from both idtracker.ai and TRex to manually reviewed data (see Table 3) shows that both solutions consistently provide high accuracy results of above 99.5% for most videos, but that TRex is slightly improved in all cases while also having a better overall frame coverage per individual (99.65% versus idtracker.ai's 97.93%, where 100% would mean that all individuals are tracked in every frame; not shown). This suggests that the splitting algorithm (see appendix, Algorithm for splitting touching individuals) is working to TRex' advantage here.

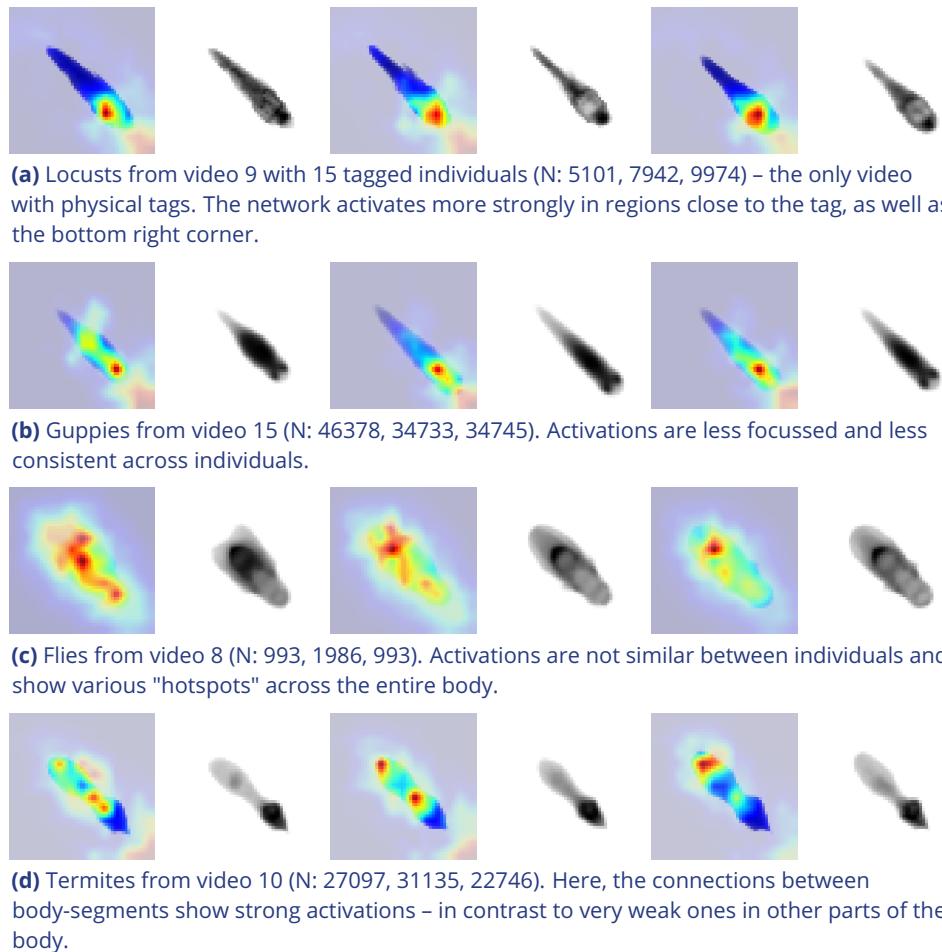


Figure 3. Activation differences for images of randomly selected individuals from four videos, next to a median image of the respective individual – which hides thin extremities, such as legs in (a) and (c). The captions in (a-d) detail the species per group and number of samples per individual. Colors represent the relative activation differences, with hotter colors suggesting bigger magnitudes, which are computed by performing a forward-pass through the network up to the last convolutional layer (using `keract`). The outputs for each identity are averaged and stretched back to the original image size by cropping and scaling according to the network architecture. Differences shown here are calculated per cluster of pixels corresponding to each filter, comparing average activations for images from the individual's class to activations for images from other classes.

Figure 3-source data 1. [Code](#), as well as images/weights needed to produce this figure (see README).

302 Additionally, while TRex could successfully track individuals in all videos without tags, we were
 303 interested to see the effect of tags (in this case QR tags attached to locusts, see **Figure 3a**) on
 304 network training. In **Figure 3** we visualise differences in network activation, depending on the
 305 visual features available for the network to learn from, which are different between species (or
 306 due to physically added tags, as mentioned above). The "hot" regions indicate larger between-
 307 class differences for that specific pixel (values are the result of activation in the last convolutional
 308 layer of the trained network, see figure legend). Differences are computed separately within each
 309 group and are not directly comparable between trials/species in value. However, the distribution
 310 of values – reflecting the network's reactivity to specific parts of the image – is. Results show that
 311 the most apparent differences are found for the stationary parts of the body (not in absolute terms,
 312 but following normalization, as shown in **Figure 8c**), which makes sense seeing as this part (i) is the
 313 easiest to learn due to it being in exactly the same position every time, (ii) larger individuals stretch
 314 further into the corners of a cropped image, making the bottom right of each image a source of
 315 valuable information (especially in **Figure 3a**/**Figure 3b** and (iii) details that often occur in the head-

video	#ind.	length	max.consec.	TRex memory (GB)	idtracker.ai memory (GB)
12	10	10min	26.03s	$\varnothing 4.88 \pm 0.23$, max 6.31	$\varnothing 8.23 \pm 0.99$, max 28.85
13	10	10min	36.94s	$\varnothing 4.27 \pm 0.12$, max 4.79	$\varnothing 7.83 \pm 1.05$, max 29.43
11	10	10min	28.75s	$\varnothing 4.37 \pm 0.32$, max 5.49	$\varnothing 6.53 \pm 4.29$, max 29.32
7	100	1min	5.97s	$\varnothing 9.4 \pm 0.47$, max 13.45	$\varnothing 15.27 \pm 1.05$, max 24.39
15	8	72min	79.4s	$\varnothing 5.6 \pm 0.22$, max 8.41	$\varnothing 35.2 \pm 4.51$, max 91.26
10	10	10min	1.91s	$\varnothing 6.94 \pm 0.27$, max 10.71	N/A
9	15	60min	7.64s	$\varnothing 13.81 \pm 0.53$, max 16.99	N/A
8	59	10min	102.35s	$\varnothing 12.4 \pm 0.56$, max 17.41	$\varnothing 35.3 \pm 0.92$, max 50.26
14	8	195min	145.77s	$\varnothing 12.44 \pm 0.8$, max 21.99	$\varnothing 35.08 \pm 4.08$, max 98.04
16	8	198min	322.57s	$\varnothing 16.15 \pm 1.6$, max 28.62	$\varnothing 49.24 \pm 8.21$, max 115.37

Table 4. Both TRex and idtracker.ai analysed the same set of videos, while continuously logging their memory consumption using an external tool. Rows have been sorted by video_length * #individuals, which seems to be a good predictor for the memory consumption of both solutions. idtracker.ai has mixed mean values, which, at low individual densities are similar to TRex' results. Mean values can be misleading here, since more time spent in low-memory states skews results. The maximum, however, is more reliable since it marks the memory that is necessary to run the system. Here, idtracker.ai clocks in at significantly higher values (almost always more than double) than TRex.

Table 4-source data 1. Data from log files for all trials as a single table, where each row is one sample. The total memory of each sample is calculated as SWAP + PRIVATE + SHARED. Each row indicates at which exact time, by which software, and as part of which trial it was taken.

316 region (like distance between the eyes) which can also play a role here. "Hot" regions in the bottom
 317 right corner of the activation images (e.g. in *Figure 3d*) suggest that also pixels are reacted to which
 318 are explicitly *not* part of the individual itself but of other individuals – likely this corresponds to the
 319 network making use of size/shape differences between them.

320 As would be expected, distinct patterns can be recognized in the resulting activations after
 321 training as soon as physical tags are attached to individuals (as in *Figure 3a*). While other parts
 322 of the image are still heavily activated (probably to benefit from size/shape differences between
 323 individuals), tags are always at least a large part of where activations concentrate. The network
 324 seemingly makes use of the additional information provided by the experimenter, where that has
 325 occurred. This suggests that, while definitely not being necessary, adding tags probably does not
 326 worsen, and likely may even improve, training accuracy, for difficult cases allowing networks to
 327 exploit any source of inter-individual variation.

328 Visual Identification: Memory Consumption

329 In order to generate comparable results between both tested software solutions, the same exte-
 330 rnal script has been used to measure shared, private and swap memory of idtracker.ai and TRex,
 331 respectively. There are a number of ways with which to determine the memory usage of a process.
 332 For automation purposes we decided to use a tool called *syrup*, which can start and save informa-
 333 tion about a specified command automatically. We modified it slightly, so we could obtain more
 334 accurate measurements for Swap, Shared and Private separately, using *ps_mem*.

335 As expected, differences in memory consumption are especially prominent for long videos (4-7x
 336 lower maximum memory), and for videos with many individuals (2-3x lower). Since we already ex-
 337 perienced significant problems tracking a long video (>3h) of only 8 individuals with idtracker.ai,
 338 we did not attempt to further study its behavior in long videos with many individuals. However, we
 339 would expect idtracker.ai's memory usage to increase even more rapidly than is visible in *Figure 4*
 340 since it retains a lot of image data (segmentation/pixels) in memory and we already had to "allow"
 341 it to relay to hard-disk in our efforts to make it work for Videos 8, 14 and 16 (which slows down
 342 analysis). The maximum memory consumption across all trials was on average 5.01 ± 2.54 times

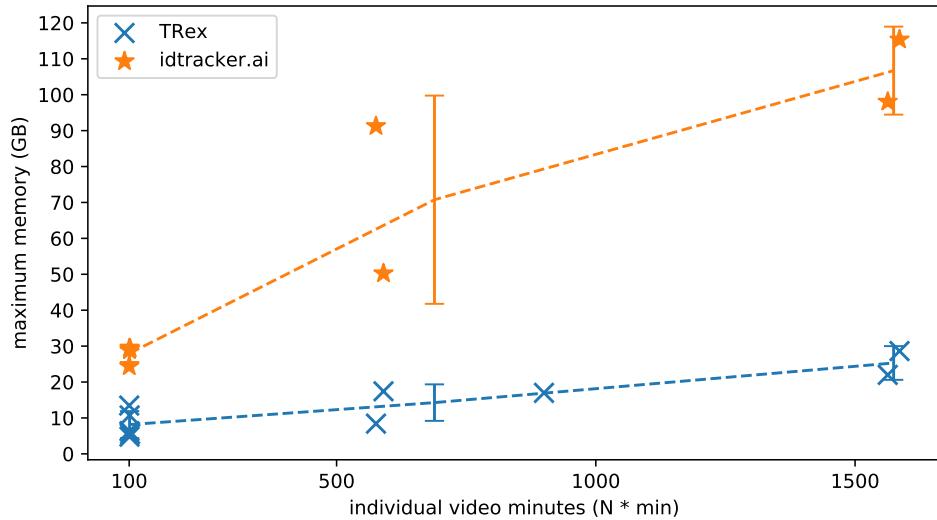


Figure 4. The maximum memory by TRex and idtracker.ai when tracking videos from a subset of all videos (the same videos as in *Table 2*). Results are plotted as a function of video length (min) multiplied by the number of individuals. We have to emphasize here that, for the videos in the upper length regions of multiple hours (16, 14), we had to set idtracker.ai to store segmentation information on disk – as opposed to in RAM. This uses less memory, but is also slower. For the video with flies we tried out both and also settled for on-disk, since otherwise the system ran out of memory. Even then, the curve still accelerates much faster for idtracker.ai, ultimately leading to problems with most computer systems. To minimize the impact that hardware compatibility has on research, we implemented switches limiting memory usage while always trying to maximize performance given the available data. TRex can be used on modern laptops and normal consumer hardware at slightly lower speeds, but without any *fatal* issues.

Figure 4-source data 1. Each data-point from *Figure 4* as plotted, indexed by video and software used.

343 higher in idtracker.ai, ranging from 1.81 to 10.85 times the maximum memory consumption of
 344 TRex for the same video.

345 Overall memory consumption for TRex also contains posture data, which contributes a lot to
 346 RAM usage. Especially with longer videos, disabling posture can lower the hardware needs for running
 347 our software. If posture is to be retained, the user can still (more slightly) reduce memory
 348 requirements by changing the outline re-sampling scale (1 by default), which adjusts the outline
 349 resolution between sub- and super-pixel accuracy. While analysis will be faster – and memory con-
 350 sumption lower – when posture is disabled (only limited by the matching algorithm, see *Appendix 4*
 351 *Figure A3*), users of the visual identification might experience a decrease in training accuracy or
 352 speed (see *Figure 5*).

353 **Visual Identification: Processing Time**

354 Automatically correcting the trajectories (to produce consistent identity assignments) means that
 355 additional time is spent on the training and application of a network, specifically for the video
 356 in question. Visual identification builds on some of the other methods described in this paper
 357 (tracking and posture estimation), naturally making it by far the most complex and time-consuming
 358 process in TRex – we thus evaluated how much time is spent on the entire sequence of all required
 359 processes. For each run of TRex and idtracker.ai, we saved precise timing information from start
 360 to finish. Since idtracker.ai reads videos *directly* and preprocesses them again each run, we used
 361 the same starting conditions with our software for a direct comparison:

362 A trial starts by converting/preprocessing a video in TGrabs and then immediately opening it in
 363 TRex, where automatic identity corrections were applied. TRex terminated automatically after sat-
 364 isfying a correctness criterion (high uniqueness value) according to equation (1). It then exported
 365 trajectories, as well as validation data (similar to idtracker.ai), concluding the trial. The sum of

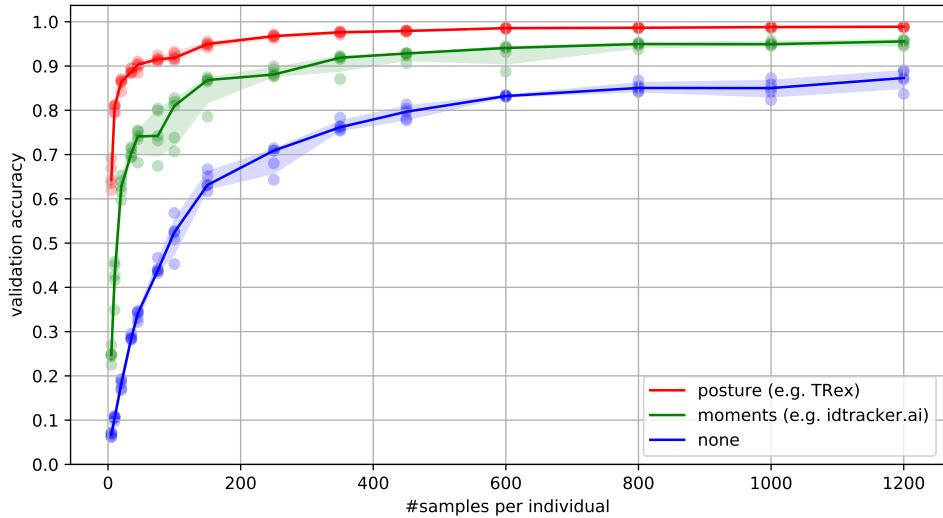


Figure 5. Convergence behavior of the network training for three different normalization methods. This shows the maximum achievable validation accuracy after 100 epochs for 100 individuals (video 7), when sub-sampling the number of examples per individual. Tests were performed using a manually corrected training dataset to generate the images in three different ways, using the same, independent script (see *Figure 8*): Using no normalization (blue), using normalization based on image moments (green, similar to *idtracker.ai*), and using posture information (red, as in *TRex*). Higher numbers of samples per individual result in higher maximum accuracy overall, but – unlike the other methods – posture-normalized runs already reach an accuracy above the 90% mark for ≥ 75 samples. This property can help significantly in situations with more crossings, when longer global segments are harder to find.

[Figure 5-source data 1. Raw data-points as plotted in Figure 5.](#)

video	# ind.	length	sample	TGrabs (min)	TRex (min)	ours (min)	idtracker.ai (min)
7	100	1min	1.61s	2.03 ± 0.02	74.62 ± 6.75	76.65	392.22 ± 119.43
8	59	10min	19.46s	9.28 ± 0.08	96.7 ± 4.45	105.98	4953.82 ± 115.92
9	15	60min	33.81s	13.17 ± 0.12	101.5 ± 1.85	114.67	N/A
11	10	10min	12.31s	8.8 ± 0.12	21.42 ± 2.45	30.22	127.43 ± 57.02
12	10	10min	10.0s	8.65 ± 0.07	23.37 ± 3.83	32.02	82.28 ± 3.83
13	10	10min	36.91s	8.65 ± 0.07	12.47 ± 1.27	21.12	79.42 ± 4.52
10	10	10min	16.22s	4.43 ± 0.05	35.05 ± 1.45	39.48	N/A
14	8	195min	67.97s	109.97 ± 2.05	70.48 ± 3.67	180.45	707.0 ± 27.55
15	8	72min	79.36s	32.1 ± 0.42	30.77 ± 6.28	62.87	291.42 ± 16.83
16	8	198min	134.07s	133.1 ± 2.28	68.85 ± 13.12	201.95	1493.83 ± 27.75

Table 5. Evaluating time-cost for automatic identity correction – comparing to results from *idtracker.ai*. Timings consist of preprocessing time in TGrabs plus network training in TRex, which are shown separately as well as combined (*ours (min)*, $N = 5$). The time it takes to analyse videos strongly depends on the number of individuals and how many usable samples per individual the initial segment provides. The length of the video factors in as well, as does the stochasticity of the gradient descent (training). *idtracker.ai* timings ($N = 3$) contain the whole tracking and training process from start to finish, using its *terminal_mode* (v3). Parameters have been manually adjusted per video and setting, to the best of our abilities, spending at most one hour per configuration. For videos 16 and 14 we had to set *idtracker.ai* to storing segmentation information on disk (as compared to in RAM) to prevent the program from being terminated for running out of memory.

[Table 5-source data 1. Preprocessed log files \(see also *notebooks.zip* in *Walter et al. \(2020\)*\) in a table format. The total processing time \(s\) of each trial is indexed by video and software used – TGrabs for conversion and TRex and idtracker.ai for visual identification. This data is also used in Appendix 4 Table A4.](#)

366 time spent within TGrabs and TRex gives the total amount of time for that trial. For the purpose of
 367 this test it would not have been fair to compare only TRex processing times to idtracker.ai, but
 368 it is important to emphasize that conversion could be skipped entirely by using TGrabs to record
 369 videos directly from a camera instead of opening an existing video file.

370 In [Table 5](#) we can see that video length and processing times (in TRex) did not correlate di-
 371 rectly. Indeed, a 1 minute video (video [8](#)) took significantly longer than one that was 60 minutes
 372 long (video [15](#)). The reason for this, initially counterintuitive, result is that the process of learning
 373 identities requires sufficiently long video sequences: longer samples have a higher likelihood of
 374 capturing more of the total possible intra-individual variance which helps the algorithm to more
 375 comprehensively represent each individual's appearance. Longer videos naturally provide more
 376 material for the algorithm to choose from and, simply due to their length, have a higher probabili-
 377 ty of containing at least one higher-quality segment that allows higher uniqueness-regimes to be
 378 reached more quickly (see [Guiding the Training Process and Stopping-criteria](#)). Thus, it is important
 379 to use sufficiently long video sequences for visual identification, and longer sequences can lead to
 380 better results – both in terms of quality and processing time.

381 Compared to idtracker.ai, TRex (conversion + visual identification) shows both considerably
 382 lower computation times (2.57x to 46.74x faster for the same video), as well as lower variance in
 383 the timings (79% lower for the same video on average).

384 Discussion

385 We have designed TRex to be a versatile and fast program that can enable researchers to track
 386 animals (and other mobile objects) in a wide range of situations. It maintains identities of up to
 387 100 un-tagged individuals and produces corrected tracks, along with posture estimation, [visual-
 388 field reconstruction, and other features that enable the quantitative study of animal behavior](#). Even
 389 videos that can not be tracked by other solutions, such as videos with over 500 animals, can now
 390 be tracked within the same day of recording.

391 While all options are available from the command-line and a screen is not required, TRex of-
 392 fers a rich, yet straight-forward to use, interface to local as well as remote users. Accompanied by
 393 the integrated documentation for all parameters, each stating purpose, type and value ranges, as
 394 well as a comprehensive online documentation, [new users are provided with all the information
 395 required for a quick adoption of our software](#). Especially to the benefit of new users, we evaluated
 396 the parameter space [using videos of diverse species](#) (fish, termites, locusts) and determined which
 397 parameters work best in most use-cases to set their default values.

398 The interface is structured into groups (see [Figure 6](#)), categorized by the typical use-case:

- 399 1. The main menu, containing options for loading/saving, options for the timeline and reanalysis
 400 of parts of the video
- 401 2. Timeline and current video playback information
- 402 3. Information about the selected individual
- 403 4. Display options and an interactive "omni-box" for viewing and changing parameters
- 404 5. General status information about TRex and the Python integration

405 The tracking accuracy of TRex is at the state-of-the-art while typically being 2.57x to 46.74x faster
 406 than comparable software and having lower hardware requirements – [especially RAM](#). In addition
 407 to visual identification and tracking, it provides a rich assortment of additional data, including body
 408 posture, visual fields, and other kinematic as well as group-related information (such as derivatives
 409 of position, border and mean neighbor distance, group compactness, etc.); even in live-tracking
 410 and closed-loop situations.

411 Raw tracking speeds (without visual identification) still achieved roughly 80% accuracy per deci-
 412 sion (as compared to >99% with visual identification). We have found that real-time performance
 413 can be achieved, even on relatively modest hardware, for all numbers of individuals ≤ 256 with-
 414 out posture estimation (≤ 128 with posture estimation). More than 256 individuals can be tracked

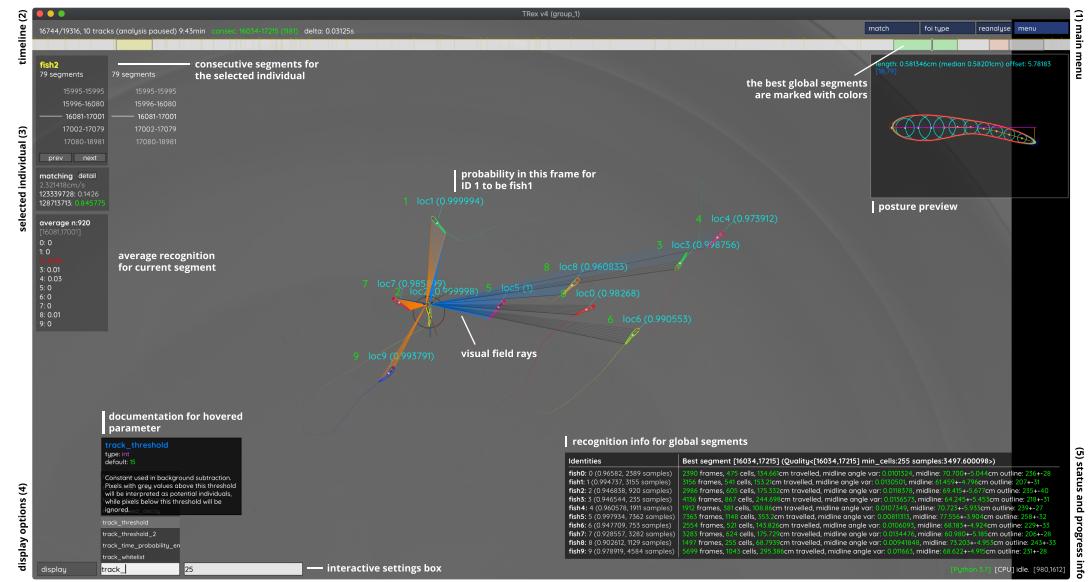


Figure 6. An overview of TRex' the main interface, which is part of the documentation at trex.run/docs. Interface elements are sorted into categories in the four corners of the screen (labelled here in black). The omni-box on the bottom left corner allows users to change parameters on-the-fly, helped by a live auto-completion and documentation for all settings. Only some of the many available features are displayed here. Generally, interface elements can be toggled on or off using the bottom-left display options or moved out of the way with the cursor. Users can customize the tinting of objects (e.g. sourcing it from their speed) to generate interesting effect and can be recorded for use in presentations. Additionally, all exportable metrics (such as border-distance, size, x/y, etc.) can also be shown as an animated graph for a number of selected objects. Keyboard shortcuts are available for select features such as loading, saving, and terminating the program. Remote access is supported and offers the same graphical user interface, e.g. in case the software is executed without an application window (for batch processing purposes).

415 as well, remarkably still delivering frame-rates at about 10-25 frames per second using the same
416 settings.

417 Not only does the increased processing-speeds benefit researchers, but the contributions we
418 provide to data exploration should not be underestimated as well – merely making data more
419 easily accessible right out-of-the-box, such as visual fields and live-heatmaps, has the potential to
420 reveal features of group- and individual behaviour which have not been visible before. TRex makes
421 information on multiple timescales of events available simultaneously, and sometimes this is the
422 only way to detect interesting properties (e.g. trail formation in termites).

423 Since the software is already actively used within the Max Planck Institute of Animal Behavior,
424 reported issues have been taken into consideration during development. However, certain theo-
425 retical, as well as practically observed, limitations remain:

- 426 • Posture: While almost all shapes can be detected correctly (by adjusting parameters), some
427 shapes – especially round shapes – are hard to interpret in terms of "tail" or "head". This
428 means that only the other image alignment method (moments) can be used. However, it
429 does introduce some limitations e.g. calculating visual fields is impossible.
- 430 • Tracking: Predictions, if the wrong direction is assumed, might go really far away from where
431 the object is. Objects are then "lost" for a fixed amount of time (parameter). This can be
432 "fixed" by shortening this time-period, though this leads to different problems when the soft-
433 ware does not wait long enough for individuals to reappear.
- 434 • General: Barely visible individuals have to be tracked with the help of deep learning (e.g.
435 using [Caelles et al. \(2017\)](#)) and a custom-made mask per video frame, prepared in an external
436 program of the users choosing
- 437 • Visual identification: All individuals have to be *visible* and *separate* at the same time, at least

438 once, for identification to work at all. Visual identification, e.g. with very high densities of
 439 individuals, can thus be very difficult. This is a hard restriction to any software since finding
 440 consecutive global segments is the underlying principle for the successful recognition of
 441 individuals.

442 We will continue updating the software, increasingly addressing the above issues (and likely
 443 others), as well as potentially adding new features. During development we noticed a couple of
 444 areas where improvements could be made, both theoretical and practical in nature. Specifically,
 445 incremental improvements in analysis speed could be made regarding visual identification by us-
 446 ing the trained network more sporadically – e.g. it is not necessary to predict every image of very
 447 long consecutive segments, since, even with fewer samples, prediction values are likely to converge
 448 to a certain value early on. A likely more potent change would be an improved "uniqueness" algo-
 449 rithm, which, during the accumulation phase, is better at predicting which consecutive segment
 450 will improve training results the most. This could be done, for example, by taking into account the
 451 variation between images of the same individual. Other planned extensions include:

- 452 • (Feature): We want to have a more general interface available to users, so they can create
 453 their own plugins. Working with the data in live-mode, while applying their own filters. As
 454 well as specifically being able to write a plugin that can detect different species/annotate
 455 them in the video.
- 456 • (Crossing solver): Additional method optimized for splitting overlapping, solid-color objects.
 457 The current method, simply using a threshold, is effective for many species but often pro-
 458 duces large holes when splitting objects consisting of largely the same color.

459 To obtain the most up-to-date version of **TRex**, please download it at trex.run or update your
 460 existing installation according to our instructions listed on trex.run/docs/install.html.

461 Materials & Methods

462 In the following sections we describe the methods implemented in **TRex** and **TGrabs**, as well as their
 463 most important features in a typical order of operations (see *Figure 2* for a flow diagram), starting
 464 out with a raw video. We will then describe how trajectories are obtained and end with the most
 465 technically involved features.

466 Segmentation

467 When an image is first received from a camera (or a video file), the objects of interest potentially
 468 present in the frame must be **found** and cropped out. Several technologies are available to sep-
 469 arate the foreground from the background (segmentation). Various machine learning algorithms
 470 are frequently used to great effect, even for the most complex environments (*Hughey et al. 2018*,
Robie et al. 2017, *Francisco et al. 2019*). These more advanced approaches are typically beneficial
 471 for the analysis of field-data or organisms that are very hard to see in video (e.g. very transpar-
 472 ent or low contrast objects/animals in the scene). In these situations, where integrated methods
 473 might not suffice, it is possible to segment objects from the background using external, e.g. deep-
 474 learning based, tools (see next paragraph). However, for most laboratory experiments, simpler
 475 (and also much faster), classical image-processing methods yield satisfactory results. Thus, we
 476 provide as a generically-useful capability **background-subtraction**, which is the default method by
 477 which objects are segmented. This can be used immediately in experiments where the background
 478 is relatively static. Backgrounds are generated automatically by uniformly sampling images from
 479 the source video(s) – different modes are available (min/max, mode and mean) for the user to
 480 choose from. More advanced image-processing techniques like luminance equalization (which is
 481 useful when lighting varies between images), image undistortion, and brightness/contrast adjust-
 482 ments are available in **TGrabs** and can enhance segmentation results – but come at the cost of
 483

484 slightly increased processing time. Importantly, since many behavioral studies rely on $\geq 4K$ resolution videos, we heavily utilize the GPU (if available) to speed up most of the image-processing, allowing TRex to scale well with increasing image resolution.

487 **TGrabs can generally find any object in the video stream, and subsequently pass it on to the tracking algorithm (next section),** as long as either (i) the background is relatively static while the objects move at least occasionally, (ii) the objects/animals of interest have enough contrast to the background or (iii) the user provides an additional binary mask per frame which is used to separate the objects of interest from the background, the typical means of doing this being by deep-learning based segmentation (e.g. *Caelles et al. 2017*). These masks are expected to be in a video-format themselves and correspond 1:1 in length and dimensions to the video that is to be analyzed. They are expected to be binary, marking individuals in white and background in black. Of course, these binary videos could be used on their own, but would not retain grey-scale information of the objects. There are a lot of possible applications where this could be useful; but generally, whenever individuals are really hard to detect visually and need to be recognized by a different software (e.g. a machine-learning-based segmentation like *Maninis et al. 2018*). Individual frames can then be connected using our software as a second step.

500 The detected objects are saved to a custom non-proprietary compressed file format (Preprocessed Video or PV, see appendix The PV file format), that stores only the most essential information from the original video stream: the objects and their pixel positions and values. This format is optimized for quick random index access by the tracking algorithm (see next section) and stores other meta-information (like frame timings) utilized during playback or analysis. When recording videos directly from a camera, they can also be streamed to an additional and independent MP4 container format (plus information establishing the mapping between PV and MP4 video frames).

507 **Tracking**

508 Once animals (or, more generally, termed "objects" henceforth) have been successfully segmented from the background, we can either use the live-tracking feature in TGrabs or open a pre-processed file in TRex, to generate the trajectories of these objects. This process uses information regarding an object's movement (i.e. its kinematics) to follow it across frames, estimating future positions based on previous velocity and angular speed. It will be referred to as "tracking" in the following text, and is a required step in all workflows.

514 Note that this approach alone is very fast, but, as will be shown, is subject to error with respect to maintaining individual identities. If that is required, there is a further step, outlined in Automatic Visual Identification Based on Machine Learning below, which can be applied at the cost of processing speed. First, however, we will discuss the general basis of tracking, which is common to approaches that do, and do not, require identities to be maintained with high-fidelity. Tracking can occur for two distinct categories, which are handled slightly differently by our software:

- 520** 1. there is a known number of objects
- 521** 2. there is an unknown number of objects

522 The first case assumes that the number of tracked objects in a frame cannot exceed a certain expected number of objects (calculated automatically, or set by the user). This allows the algorithm to make stronger assumptions, for example regarding noise, where otherwise "valid" objects (conforming to size expectations) are ignored due to their positioning in the scene (e.g. too far away from previously lost individuals). In the second case, new objects may be generated until all viable objects in a frame are assigned. While being more susceptible to noise, this is useful for tracking a large number of objects, where counting objects may not be possible, or where there is a highly variable number of objects to be tracked.

530 For a given video, our algorithm processes every frame sequentially, extending existing trajectories (if possible) for each of the objects found in the current frame. Every object can only be assigned to one trajectory, but some objects may not be assigned to any trajectory (e.g. in case the

533 number of objects exceeds the allowed number of individuals) and some trajectories might not
 534 be assigned to any object (e.g. while objects are out of view). To estimate object identities across
 535 frames we use an approach akin to the popular Kalman filter (*Kalman, 1960*) which makes pre-
 536 dictions based on multiple noisy data streams (here, positional history and posture information).
 537 In the initial frame, objects are simply assigned from top-left to bottom-right. In all other frames,
 538 assignments are made based on probabilities (see appendix Matching an object to an object in the
 539 next frame) calculated for every combination of object and trajectory. These probabilities repre-
 540 sent the degree to which the program believes that "it makes sense" to extend an existing trajectory
 541 with an object in the current frame, given its position and speed. Our tracking algorithm only con-
 542 siders assignments with probabilities larger than a certain threshold, generally constrained to a
 543 certain proximity around an object assigned in the previous frame.

544 Matching a set of objects in one frame with a set of objects in the next frame is representative
 545 of a typical assignment problem, which can be solved in polynomial time (e.g. using the Hungar-
 546 ian method *Kuhn 1955*). However, we found that, in practice, the computational complexity of
 547 the Hungarian method can constrain analysis speed to such a degree that we decided to imple-
 548 ment a custom algorithm, which we term tree-based matching, which has a better *average-case*
 549 performance (see evaluation), even while having a comparatively bad *worst-case* complexity. Our
 550 algorithm constructs a tree of all possible object/trajecotry combinations in the frame and tries to
 551 find a compatible (such that no objects/trajectories are assigned twice) set of choices, maximizing
 552 the sum of probabilities amongst these choices (described in detail in the appendix Matching an
 553 object to an object in the next frame). Problematic are situations where a large number of objects
 554 are in close proximity of one another, since then the number of possible sets of choices grows ex-
 555 ponentially. These situations are avoided by using a mixed approach: tree-based matching is used
 556 most of the time, but as soon as the combinatorical complexity of a certain situation becomes too
 557 great, our software falls back on using the Hungarian method. If videos are known to be prob-
 558 lematic throughout (e.g. with >100 individuals consistently very close to each other), the user may
 559 choose to use an approximate method instead (described in the appendix **section 4**), which simply
 560 iterates through all objects and assigns each to the trajectory for which it has the highest proba-
 561 bility and subsequently does not consider whether another object has an even higher probability
 562 for that trajectory. While the approximate method scales better with an increasing number of in-
 563 dividuals, it is "wrong" (seeing as it does not consider all possible combinations) – which is why it is
 564 not recommended unless strictly necessary. However, since it does not consider all combinations,
 565 making it more sensitive to parameter choice, it scales better for very large numbers of objects and
 566 produces results good enough for it to be useful in very large groups (see **Appendix 4 Table A2**).

567 Situations where objects/individuals are touching, partly overlapping, or even completely over-
 568 lapping, is an issue that all tracking solutions have to deal with in some way. The first problem is the
 569 *detection* of such an overlap/crossing, the second is its *resolution*. *idtracker.ai*, for example, deals
 570 only with the first problem: It trains a neural network to detect crossings and essentially ignores
 571 the involved individuals until the problem is resolved by movement of the individuals themselves.
 572 However, using such an image-based approach can never be fully independent of the species or
 573 even video (it has to be retrained for each specific experiment) while also being time-costly to use.
 574 In some cases the size of objects might indicate that they contain multiple overlapping objects,
 575 while other cases might not allow for such an easy distinction – e.g. when sexually dimorphic ani-
 576 mals (or multiple species) are present at the same time. We propose a method, similar to *xyTracker*
 577 in that it uses the object's movement history to detect overlaps. If there are fewer objects in a re-
 578 gion than would be expected by looking at previous frames, an attempt is made to split the biggest
 579 ones in that area. The size of that area is estimated using the maximal speed objects are allowed to
 580 travel per frame (parameter, see documentation *track_max_speed*). This, of course, requires rela-
 581 tively good predictions or, alternatively, high frame-rates relative to the object's movement speeds
 582 (which are likely necessary anyway to observe behavior at the appropriate time-scales).

583 By default, objects suspected to contain overlapping individuals are split by thresholding their

584 background-difference image (see appendix **section 11**), continuously increasing the threshold un-
 585 til the expected number (or more) similarly sized objects are found. Greyscale values and, more
 586 generally, the shading of three-dimensional objects and animals often produces a natural gradia-
 587 ent (see for example **Figure 8**) making this process surprisingly effective for many of the species
 588 we tested with. Even when there is almost no visible gradient and thresholding produces holes in-
 589 side objects, objects are still successfully separated with this approach. Missing pixels from inside
 590 the objects can even be regenerated afterwards. The algorithm fails, however, if the remaining
 591 objects are too small or are too different in size, in which case the overlapping objects will not be
 592 assigned to any trajectory until all involved objects are found again separately in a later frame.

593 After an object is assigned to a specific trajectory, two kinds of data (posture and visual-fields)
 594 are calculated and made available to the user, which will each be described in one of the follow-
 595 ing subsections. In the last subsection, we outline how these can be utilized in real-time tracking
 596 situations.

597 Posture Analysis

598 Groups of animals are often modeled as systems of simple particles (*Inada and Kawachi 2002, Cav-*
599 agna et al. 2010, Pérez-Escudero and de Polavieja 2011), a reasonable simplification which helps
 600 to formalize/predict behavior. However, intricate behaviors, like courtship displays, can only be
 601 fully observed once the body shape and orientation are considered (e.g. using tools such as Deep-
 602 PoseKit, *Graving et al. 2019*, LEAP *Pereira et al. (2019)*/SLEAP *Pereira et al. (2020)*, and DeepLab-
 603 Cut, *Mathis et al. 2018*). TRex does not track individual body parts apart from the head and tail
 604 (where applicable), but even the included simple and fast 2D posture estimator already allows for
 605 deductions to be made about how an animal is positioned in space, bent and oriented – crucial
 606 e.g. when trying to estimate the position of eyes/antennae as part of an analysis, where this is
 607 required (e.g. *Strandburg-Peshkin et al. 2013, Rosenthal et al. 2015*). When detailed tracking of
 608 all extremities is required, TRex offers an option that allows it to interface with third-party soft-
 609 ware like DeepPoseKit (*Graving et al. 2019*), SLEAP (*Pereira et al. 2020*), or DeepLabCut (*Mathis*
610 et al. 2018). This option (`output_image_per_tracklet`), when set to true, exports cropped and (op-
 611 tionally) normalised videos per individual that can be imported directly into these tools – where
 612 they might perform better than the raw video. Normalisation, for example, can make it easier for
 613 machine-learning algorithms in these tools to learn where body-parts are likely to be (see **Figure 5**)
 614 and may even reduce the number of clicks required during annotation.

615 In TRex, the 2D posture of an animal consists of (i) an outline around the outer edge of a blob,
 616 (ii) a center-line (or midline for short) that curves with the body and (iii) positions on the outline that
 617 represent the front and rear of the animal (typically head and tail). Our only assumptions here are
 618 that the animal is bilateral with a mirror-axis through its center and that it has a beginning and an
 619 end, and that the camera-view is roughly perpendicular to this axis. This is true for most animals,
 620 but may not hold e.g. for jellyfish (with radial symmetry) or animals with different symmetries (e.g.
 621 radiolaria (protozoa) with spherical symmetry). Still, as long as the animal is not exactly circular
 622 from the perspective of the camera, the midline will follow its longest axis and a posture can be
 623 estimated successfully. The algorithm implemented in our software is run for every (cropped out)
 624 image of an individual and processes it as follows:

625 i. A tree-based approach follows edge pixels around an object in a clock-wise manner. Drawing
 626 the line *around* pixels, as implemented here, instead of through their centers, as done in compa-
 627 rable approaches, helps with very small objects (e.g. one single pixel would still be represented as
 628 a valid outline, instead of a single point).

629 ii. The pointiest end of the outline is assumed, by default, to be either the tail or the head
 630 (based on curvature and area between the outline points in question). Assignment of head vs. tail
 631 can be set by the user, seeing as some animals might have "pointier" heads than tails (e.g. termite
 632 workers, one of the examples we employ). Posture data coming directly from an image can be very
 633 noisy, which is why the program offers options to simplify outline shapes using an Elliptical Fourier

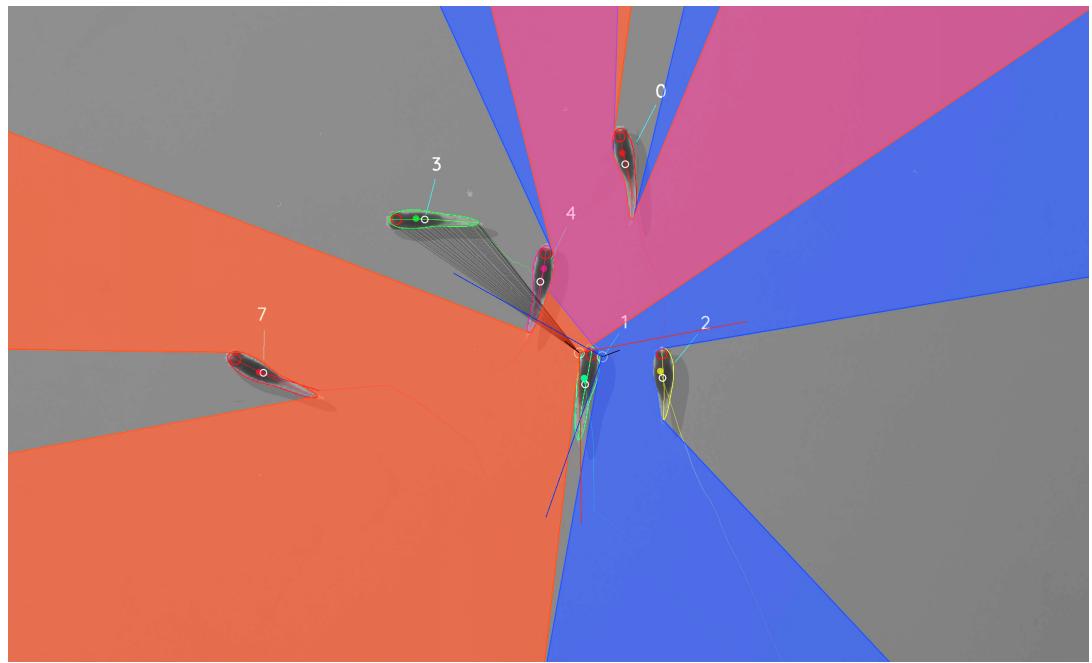


Figure 7. Visual field estimate of the individual in the center (zoomed in, the individuals are approximately 2-3cm long, video 15). Right (blue) and left (orange) fields of view intersect in the binocular region (pink). Most individuals can be seen directly by the focal individual (1, green), which has a wide field of view of 260° per eye. Individual 3 on the top-left is not detected by the focal individual directly and not part of its first-order visual field. However, second-order intersections (visualized by grey lines here) are also saved and accessible through a separate layer in the exported data.

Figure 7-video 1. A clip from video 15, showing TRex' visual-field estimation for Individual 1.

https://youtu.be/yEO_3IpZlzU

634 Transform (EFT, see *Iwata et al. 2015, Kuhl and Giardina 1982*) or smoothing via a simple weighted
 635 average across points of the curve (inspired by common subdivision techniques, see *Warren and*
 636 *Weimer 2001*). The EFT allows for the user to set the desired level of approximation detail (via the
 637 number of elliptic fourier descriptors, EFDs) and thus make it "rounder" and less jittery. Using an
 638 EFT with just two descriptors is equivalent to fitting an ellipse to the animal's shape (as, for example,
 639 xyTracker does), which is the simplest supported representation of an animal's body.

640 iii. The reference-point chosen in (ii) marks the start for the midline-algorithm. It walks both left
 641 and right from this point, always trying to move approximately the same distance on the outline
 642 (with limited wiggle-room), while at the same time minimizing the distance from the left to the right
 643 point. This works well for most shapes and also automatically yields distances between a midline
 644 point and its corresponding two points on the outline, estimating thickness of this object's body at
 645 this point.

646 Compared to the tracking itself, posture estimation is a time-consuming process and can be
 647 disabled. It is, however, required to estimate – and subsequently normalize – an animal's orientation
 648 in space (e.g. required later in Automatic Visual Identification Based on Machine Learning), or
 649 to reconstruct their visual field as described in the following sub-section.

650 Reconstructing 2D Visual Fields

651 Visual input is an important modality for many species (e.g. fish *Strandburg-Peshkin et al. 2013,*
 652 *Bilotta and Saszik 2001* and humans *Colavita 1974*). Due to its importance in widely used model
 653 organisms like zebrafish (*Danio rerio*), we decided to include the capability to conduct a 2-dimensional
 654 reconstruction of each individual's visual field as part of the software. The requirements for this
 655 are successful posture estimation and that individuals are viewed from above, as is usually the
 656 case in laboratory studies.

657 The algorithm makes use of the fact that outlines have already been calculated during posture
 658 estimation. Eye positions are estimated to be evenly distanced from the "snout" and will be spaced
 659 apart depending on the thickness of the body at that point (the distance is based on a ratio, relative
 660 to body-size, which can be adjusted by the user). Eye orientation is also adjustable, which influ-
 661 ences the size of the stereoscopic part of the visual field. We then use ray-casting to intersect rays
 662 from each of the eyes with all other individuals as well as the focal individual itself (self-occlusion).
 663 Individuals not detected in the current frame are approximated using the last available posture.
 664 Data are organized as a multi-layered 1D-image of fixed size for each frame, with each image pre-
 665 presenting angles from -180° to 180° for the given frame. Simulating a limited field-of-view would
 666 thus be as simple as cropping parts of these images off the left and right sides. The different layers
 667 per pixel encode:

- 668 1. identity of the occluder
- 669 2. distance to the occluder
- 670 3. body-part that was hit (distance from the head on the outline in percent)

671 While the individuals viewed from above on a computer screen look 2-dimensional, one major
 672 disadvantage of any 2D approach is, of course, that it is merely a projection of the 3D scene. Any
 673 visual field estimator has to assume that, from an individual's perspective, other individuals act
 674 as an occluder in all instances (see [Figure 7](#)). This may only be partly true in the real world, de-
 675 pending on the experimental design, as other individuals may be able to move slightly below, or
 676 above, the focal individuals line-of-sight, revealing otherwise occluded conspecifics behind them.
 677 We therefore support multiple occlusion-layers, allowing second-order and N th-order occlusions
 678 to be calculated for each individual.

679 Realtime Tracking Option for Closed-Loop Experiments

680 Live tracking is supported, as an option to the user, during the recording, or conversion, of a video
 681 in `TGrabs`. When closed-loop feedback is enabled, `TGrabs` focusses on maintaining stable recording
 682 frame-rates and may not track recorded frames if tracking takes too long. This is done to ensure
 683 that the recorded file can later be tracked again in full/with higher accuracy (thus no information is
 684 lost) if required, and to help the closed-loop feedback to stay synchronized with real-world events.

685 During development we worked with a mid-range gaming computer and Basler cameras at
 686 90fps and 2048^2 px resolution, where drawbacks did not occur. [Running the program on hardware](#)
 687 [with specifications below our recommendations \(see Results\)](#), however, may affect frame-rates as
 688 [described below](#).

689 `TRex` loads a prepared `Python` script, handing down an array of data per individual in every
 690 frame. Which data fields are being generated and sent to the script is selected by the script. Avail-
 691 able fields are:

- 692 • Position
- 693 • Midline information
- 694 • Visual field

695 If the script ([or any other part of the recording process](#)) takes too long to execute [in one](#) frame,
 696 [consecutive frames may be](#) dropped until a stable frame-rate can be achieved. This scales well for
 697 all computer-systems, [but results in fragmented tracking data, causing worse identity assignment](#),
 698 and reduces the number of frames and quality of data available for closed-loop feedback. However,
 699 since even untracked frames are saved to disk, these inaccuracies can be fixed in `TRex` later. Alter-
 700 natively, if live-tracking is enabled but closed-loop feedback is disabled, the program maintains
 701 [detected objects in memory and tracks them in an asynchronous thread \(potentially introducing](#)
 702 [wait time after the recording stops](#)). When the program terminates, the tracked individual's data
 703 are exported – along with a `results` file that can be loaded by the `tracker` at a later time.

704 In order to make this interface easy to use for prototyping and to debug experiments, the script
 705 may be changed during its run-time and will be reloaded if necessary. Errors in the Python code
 706 lead to a temporary pause of the closed-loop part of the program (not the recording) until all errors
 707 have been fixed.

708 Additionally, thanks to Python being a fully-featured scripting language, it is also possible to
 709 call and send information to other programs during real-time tracking. Communication with other
 710 external programs may be necessary whenever easy-to-use Python interfaces are not available for
 711 e.g. hardware being used by the experimenter.

712 Automatic Visual Identification Based on Machine Learning

713 Tracking, when it is only based on individual's positional history, can be very accurate under good
 714 circumstances and is currently the fastest way to analyse video recordings or to perform closed-
 715 loop experiments. However, such tracking methods simply do not have access to enough informa-
 716 tion to allow them to ensure identities are maintained for the duration of most entire trials – small
 717 mistakes can and will happen. There are cases, e.g. when studying polarity (only based on short
 718 trajectory segments), or other general group-level assessments, where this is acceptable and iden-
 719 tities do not have to be maintained perfectly. However, consistent identities are required in many
 720 individual-level assessments, and with no baseline truth available to correct mistakes, errors start
 721 accumulating until eventually all identities are fully shuffled. Even a hypothetical, *perfect* tracking
 722 algorithm will not be able to yield correct results in all situations as multiple individuals might go
 723 out of view at the same time (e.g. hiding under cover or just occluded by other animals). There is
 724 no way to tell who is whom, once they re-emerge.

725 The only way to solve this problem is by providing an independent source of information from
 726 which to infer identity of individuals, which is of course a principle we make use of all the time in
 727 our everyday lives: Facial identification of con-specifics is something that is easy for most humans,
 728 to an extent where we sometimes recognize face-like features where there aren't any. Our natural
 729 tendency to find patterns enables us to train experts on recognizing differences between animals,
 730 even when they belong to a completely different taxonomic order. Tracking individuals is a de-
 731 manding task, especially with large numbers of moving animals (*Liu et al. 2009* shows humans to
 732 be effective for up to 4 objects). Human observers are able to solve simple memory recall tasks
 733 for 39 objects at only 92% correct (see *Humphrey and Khan 1992*), where the presented objects
 734 do not even have to be identified individually (just classified as old/new) and contain more inher-
 735 ent variation than most con-specific animals would. Even with this being true, human observers
 736 are still the most efficient solution in some cases (e.g. for long-lived animals in complex habitats).
 737 Enhancing visual inter-individual differences by attaching physical tags is an effective way to make
 738 the task easier and more straight-forward to automate. RFID tags are useful in many situations,
 739 but are also limited since individuals have to be in very close proximity to a sensor in order to be
 740 detected (*Bonter and Bridge, 2011*). Attaching fiducial markers (such as QR codes) to animals al-
 741 lows for a very large number (thousands) of individuals to be uniquely identified at the same time
 742 (see *Gernat et al. 2018, Wild et al. 2020, Mersch et al. 2013, Crall et al. 2015*) – and over a much
 743 greater distance than RFID tags. Generating codes can also be automated, generating tags with
 744 optimal visual inter-marker distances (*Garrido-Jurado et al., 2016*), making it feasible to identify a
 745 large number of individuals with minimal tracking mistakes.

746 While physical tagging is often an effective method by which to identify individuals, it requires
 747 animals to be caught and manipulated, which can be difficult (*Mersch et al., 2013*) and is subject
 748 to the physical limitations of the respective system. Tags have to be large enough so a program
 749 can recognize it in a video stream. Even worse, especially with increased relative tag-size, the an-
 750 imal's behavior may be affected by the presence of the tag or during its application (*Dennis et al.*
 751 *2008, Pankiw and Page 2003, Sockman and Schwabl 2001*), and there might be no way for experi-
 752 menters to necessarily know that it did (unless with considerable effort, see *Switzer and Combes*
 753 *2016*). In addition, for some animals, like fish and termites, attachment of tags that are effective

754 for discriminating among a large number of individuals can be problematic, or impossible.
 755 Recognizing such issues, (**Pérez-Escudero et al., 2014**) first proposed an algorithm termed *id-*
 756 *tracker*, generalizing the process of pattern recognition for a range of different species. Training an
 757 expert program to tell individuals apart, by detecting slight differences in patterning on their bod-
 758 ies, allows the correction of identities without any human involvement. Even while being limited
 759 to about 15 individuals per group, this was a very promising approach. It became much improved
 760 upon only a few years later by the same group in their software *idtracker.ai* (**Romero-Ferrero**
 761 **et al., 2019**), implementing a paradigm shift from explicit, hard-coded, color-difference detection
 762 to using more general machine learning methods instead – increasing the supported group size
 763 by an order of magnitude.

764 We employ a method for visual identification in TRex that is similar to the one used in *idtracker.*
 765 *ai*, where a neural network is trained to visually recognize individuals and is used to correct tracking
 766 mistakes automatically, without human intervention – the network layout (see **Figure 1c**) is almost
 767 the same as well (differing only by the addition of a pre-processing layer and using 2D- instead
 768 of 1D-dropout layers). However, in TRex, processing speed and chances of success are improved
 769 (the former being greatly improved) by (i) minimizing the variance landscape of the problem and
 770 (ii) exploring the landscape to our best ability, optimally covering all poses and lighting-conditions
 771 an individual can be in, as well as (iii) shortening the training duration by significantly altering the
 772 training process – e.g. choosing new samples more adaptively and using different stopping-criteria
 773 (accuracy, as well as speed, are part of the later evaluation).

774 While Tracking already *tries* to (within each trajectory) consistently follow the same individual,
 775 there is no way to ensure/check the validity of this process without providing independent identity
 776 information. Generating this source of information, based on the visual appearance of individu-
 777 als, is what the algorithm for visual identification, described in the following subsections, aims to
 778 achieve. Re-stated simply, the goal of using automatic visual identification is to obtain reliable pre-
 779 dictions of the identities of all (or most) objects in each frame. Assuming these predictions are of
 780 sufficient quality, they can be used to detect and correct potential mistakes made during Tracking
 781 by looking for identity switches within trajectories. Ensuring that predicted identities within trajec-
 782 tories are consistent, by proxy, also ensures that each trajectory is consistently associated with a
 783 single, real individual. In the following, before describing the four stages of that algorithm, we will
 784 point out key aspects of how tracking/image data are processed and how we addressed the points
 785 (i)-(iii) above and especially highlight the features that ultimately improved performance compared
 786 to other solutions.

787 Preparing Tracking-Data

788 Visual identification starts out only with the trajectories that the Tracking provides. Tracking, on
 789 its own, is already an improvement over other solutions, especially since (unlike e.g. *idtracker.*
 790 *ai*) TRex makes an effort to separate overlapping objects (see the Algorithm for splitting touching
 791 individuals) and thus is able to keep track of individuals for longer (see **Appendix 4 Figure A2**).
 792 Here, we – quite conservatively – assume that, after every problematic situation (defined in the
 793 list below), the assignments made by our tracking algorithm are wrong. Whenever a problematic
 794 situation is encountered as part of a trajectory, we split the trajectory at that point. This way,
 795 all trajectories of all individuals in a video become an assortment of trajectory snippets (termed
 796 "segments" from here on), which are clear of problematic situations, and for each of which the
 797 goal is to find the correct identity ("correct" meaning that identities are consistently assigned to
 798 the same *real* individual throughout the video). Situations are considered "problematic", and cause
 799 the trajectory to be split, when:

- 800 • **The individual has been lost for at least one frame.** For example when individuals are
 801 moving unexpectedly fast, are occluded by other individuals/the environment, or simply not
 802 present anymore (e.g. eaten).

- 803 • **Uncertainty of assignment was too high (> 50%)** e.g. due to very high movement speeds
804 or extreme variation in size between frames. With simpler tracking tasks in mind, these seg-
805 ments are kept as *connected tracks*, but regarded as separate ones here.
- 806 • **Timestamps suggest skipped frames.** Missing frames in the video may cause wrong as-
807 signments and are thus treated as if the individuals have been lost. This distinction can only
808 be made if accurate frame timings are available (when recording using `TGabs` or provided
809 alongside the video files in separate `npz` files).

810 Unless one of the above conditions becomes true, a segment is assumed to be consecutive
811 and connected; that is, throughout the whole segment, no mistakes have been made that lead to
812 identities being switched. Frames where all individuals are currently within one such segment at
813 the same time will henceforth be termed *global segments*.

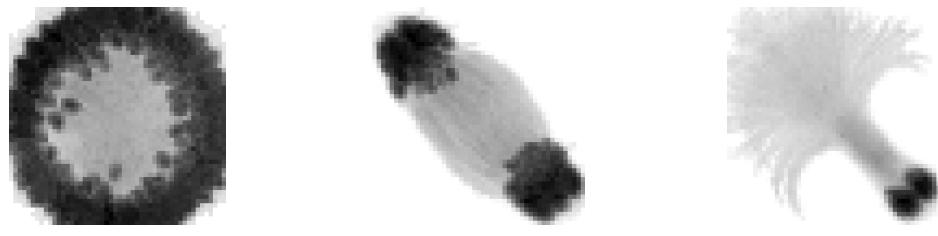
814 Since we know that there are no problematic situations inside each per-individual segment, and
815 thus also not across individuals within the range of a global segment, we can choose any global
816 segment as a basis for an initial, arbitrary assignment of identities to trajectories. One of the most
817 important steps of the identification algorithm then becomes deciding which global segment is
818 the best starting point for the training. If a mistake is made here, consecutive predictions for other
819 segments will fail and/or produce unreliable results in general.

820 Only a limited set of global segments is kept – striking a balance between respecting user-given
821 constraints and capturing as much of the variance as possible. In many of the videos used for
822 evaluation, we found that only few segments had to be considered – however, computation time
823 is ultimately bounded by reducing the number of qualifying segments. While this is true, it is also
824 beneficial to avoid auto-correlation by incorporating samples from all sections of the video instead
825 of only sourcing them from a small portion – to help achieve a balance, global segments are binned
826 by their middle frame into four bins (each quarter of the video being a bin) and then reducing the
827 number of segments inside each bin. With that goal in mind, we sort the segments within bins by
828 their "quality" – a combination of two factors:

- 829 1. To capture as much as possible the variation due to an individual's own movement, as well as
830 within the background that it moves across, a "good" segment should be a segment where
831 all individuals move as much as possible and also travel as large a distance as possible. Thus,
832 we derive a per-individual *spatial coverage descriptor* for the given segment by dissecting the
833 arena (virtually) into a grid of equally sized, rectangular "cells" (depending on the aspect ratio
834 of the video). Each time an individual's center-point moves from one cell to the next, a counter
835 is incremented for that individual. To avoid situations where, for example, all individuals but
836 one are moving, we only use the lowest per-individual spatial coverage value to represent a
837 given segment.
- 838 2. It is beneficial to have more examples for the network to learn from. Thus, as a second sorting
839 criterion, we use the average number of samples per individual.

840 After being sorted according to these two metrics, the list of segments per bin is reduced, ac-
841 cording to a user-defined variable (4 by default), leaving only the most viable options per quarter
842 of video.

843 The number of visited cells may, at first, appear to be essentially equivalent to a spatially nor-
844 malized *distance travelled* (as used in `idtracker.ai`). In edge cases, where individuals never stop
845 or always stop, both metrics can be very similar. However, one can imagine an individual continu-
846 ously moving around in the same corner of the arena, which would be counted as an equally good
847 segment for that individual as if it had traversed the whole arena (and thus capturing all variable en-
848 vironmental factors). In most cases, using highly restricted movement for training is problematic,
849 and worse than using a shorter segment of the individual moving diagonally through the entire
850 space, since the latter captures more of the variation within background, lighting conditions and
851 the animals movement in the process.



(a) No normalization.

(b) Using the main body-axis (moments).

(c) Using posture information.

Figure 8. Comparison of different normalization methods. Images all stem from the same video and belong to the same identity. The video has previously been automatically corrected using the visual identification. Each object visible here consists of N images $M_i, i \in [0, N]$ that have been accumulated into a single image using $\min_{i \in [0, N]} M_i$, with min being the element-wise minimum across images. The columns represent same samples from the same frames, but normalized in three different ways: In (a), images have not been normalized at all. Images in (b) have been normalized by aligning the objects along their main axis (calculated using *image-moments*), which only gives the axis within 0 to 180 degrees. In (c), all images have been aligned using posture information generated during the tracking process. As the images become more and more recognizable to us from left to right, the same applies to a network trying to tell identities apart: Reducing noise in the data speeds up the learning process.

852 Minimizing the Variance Landscape by Normalizing Samples

853 A big strength of machine learning approaches is their resistance to noise in the data. Generally,
 854 any machine learning method will likely still converge - even with noisy data. Eliminating unnec-
 855 essary noise and degrees of freedom in the dataset, however, will typically help the network to
 856 converge much more quickly: Tasks that are easier to solve will of course also be solved more ac-
 857 curately within similar or smaller timescales. This is due to the optimizer not having to consider
 858 various parts of the possible parameter-space during training, or, put differently, shrinking the
 859 overall parameter-space to the smallest possible size without losing important information. The
 860 simplest such optimization included in most tracking and visual identification approaches is to seg-
 861 ment out the objects and centering the individuals in the cropped out images. This means that (i)
 862 the network does not have to consider the whole image, (ii) needs only to consider one individual
 863 at a time and (iii) the corners of the image can most likely be neglected.

864 Further improving on this, approaches like *idtracker.ai* align all objects along their most-
 865 elongated axis, essentially removing global orientation as a degree of freedom. The orientation of
 866 an arbitrary object can be calculated e.g. using an approach often referred to as *image-moments*
 867 (*Hu, 1962*), yielding an angle within $[0 - 180]^\circ$. Of course, this means that

- 868 1. circular objects have a random (noisy) orientation
- 869 2. elongated objects (e.g. fish) can be either head-first or flipped by 180° and there is no way to
 870 discriminate between those two cases (see second row, **Figure 8**)
- 871 3. a C-shaped body deformation, for example, results in a slightly bent axis, meaning that the
 872 head will not be in exactly the same position as with a straight posture of the animal.

873 Each of these issues adds to the things the network has to learn to account for, widening the
 874 parameter-space to be searched and increasing computation time. However, barring the first point,
 875 each problem can be tackled using the already available posture information. Knowing head and
 876 tail positions and points along the individual's center-line, the individual's heads can be locked
 877 roughly into a single position. This leaves room only for their rear end to move, reducing variation
 878 in the data to a minimum (see **Figure 8**). In addition to faster convergence, this also results in
 879 better generalization right from the start and even with a smaller number of samples per individual
 880 (see **Figure 5**). **For further discussion of highly deformable bodies, such as of rodents, please see**
 881 **Appendix** (Posture and Visual Identification of Highly-Deformable Bodies).

895 Box 1. Calculating uniqueness for a frame

```

896 Data: frame  $x$ 
897 Result: Uniqueness score for frame  $x$ 
898 uids = map{}
899  $\hat{p}(i \mid b)$  is the probability of blob  $b$  to be identity  $i$ 
900  $f(x)$  returns a list of the tracked objects in frame  $x$ 
901  $E(v) = (1 + \exp(-\pi)) / (1 + \exp(-\pi v))$  is a shift of roughly +0.5 and non-linear scaling of
902 values  $0 \leq v \leq 1$ 
903
904 foreach object  $b \in f(x)$  do
905   maxid =  $\arg \max_i \hat{p}(i \mid b)$  with  $i \in$  identities
911   if maxid  $\in$  uids then
906     | uids[maxid] =  $\max(\text{uids}[\text{maxid}], \hat{p}(\text{maxid}, b))$ 
907   else
908     | uids[maxid] =  $\hat{p}(\text{maxid}, b)$ 
909   end
910 end
911 return  $|\text{uids}|^{-1} |f(x)| * E(|\text{uids}|^{-1} (\sum_{i \in \text{uids}} \text{uids}[i]))$ 

```

Algorithm 1: The algorithm used to calculate the uniqueness score for an individual frame.

Probabilities $\hat{p}(i \mid b)$ are predictions by the pre-trained network. During the accumulation these predictions will gradually improve proportional to the global training quality. Multiplying the unique percentage $|\text{uids}|^{-1} |f(x)|$ by the (scaled) mean probability deals with cases of low accuracy, where individuals switch every frame (but uniquely).

882 Guiding the Training Process

883 Per batch, the stochastic gradient descent is directed by the local accuracy (a fraction of correct/total
884 predictions), which is a simple and commonly used metric that has no prior knowledge of where
885 the samples within a batch come from. This has the desirable consequence that no knowledge
886 about the temporal arrangement of images is necessary in order to train and, more importantly,
887 to apply the network later on.

888 In order to achieve accurate results quickly across batches, while at the same time making it pos-
889 sible to indicate to the user potentially problematic sequences within the video, we devised a metric
890 that can be used to estimate local as well as global training quality: We term this uniqueness and
891 it combines information about objects within a frame, following the principle of non-duplication;
892 images of individuals within the same frame are required to be assigned different identities by the
893 networks predictions.

894 The program generates image data for evenly spaced frames across the entire video. All images
895 of tracked individuals within the selected frames are, after every epoch of the training, passed on
896 to the network. It returns a vector of probabilities p_{ij} for each image i to be identity $j \in [0, N]$, with
897 N being the number of individuals. Based on these probabilities, uniqueness can be calculated as
898 in Box 1, evenly covering the entire video. The magnitude of this probability vector per image is
899 taken into account, rewarding strong predictions of $\max_j \{p_{ij}\} = 1$ and punishing weak predictions
900 of $\max_j \{p_{ij}\} < 1$.

901 Uniqueness is not integrated as part of the loss function, but it is used as a global gradient
902 before and after each training unit in order to detect global improvements. Based on the average
903 uniqueness calculated before and after a training unit, we can determine whether to stop the train-
904 ing, or whether training on the current segment made our results worse (faulty data). If uniqueness
905 is consistently high throughout the video, then training has been successful and we may terminate

924 early. Otherwise, valleys in the uniqueness curve indicate bad generalization and thus currently
 925 missing information regarding some of the individuals. In order to detect problematic sections of
 926 the video we search for values below $1 - \frac{0.5}{N}$, meaning that the section potentially contains new
 927 information we should be adding to our training data. Using accuracy per-batch and then using
 928 uniqueness to determine global progress, we get the best of both worlds: A context-free prediction
 929 method that is trained on global segments that are strategically selected by utilizing local context
 930 information.

931 The closest example of such a procedure in `idtracker.ai` is the termination criterion after
 932 *protocol 1*, which states that individual segments have to be consistent and certain enough in all
 933 global segments in order to stop iterating. While this seems to be similar at first, the way accu-
 934 racy is calculated and the terminology here are quite different: (i) Every metric in `idtracker.ai`'s
 935 final assessment after *protocol 1* is calculated at segment-level, not utilizing per-frame information.
 936 *Uniqueness* works per-frame, not per segment, and considers individual frames to be entirely inde-
 937 pendent from each other. It can be considered a much stronger constraint set upon the network's
 938 predictive ability, seeing as it basically counts the number of times mistakes are estimated to have
 939 happened within single frames. Averaging only happens *afterwards*. (ii) The terminology of iden-
 940 tities being unique is only used in `idtracker.ai` once after *protocol 1* and essentially as a binary
 941 value, not recognizing its potential as a descendable gradient. Images are simply added until a
 942 certain percentage of images has been reached, at which point accumulation is terminated. (iii)
 943 Testing uniqueness is much faster than testing network accuracy across segments, seeing as the
 944 same images are tested over and over again (meaning they can be cached) and the testing dataset
 945 can be much smaller due to its locality. *Uniqueness* thus provides a stronger gradient estimation,
 946 while at the same time being more local (meaning it can be used independently of whether images
 947 are part of global segments), as well as more manageable in terms of speed and memory size.

948 In the next four sections, we describe the training phases of our algorithm (1-3), and how the
 949 successfully trained network can be used to automatically correct trajectories based on its predic-
 950 tions (4).

951 1. The Initial Training Unit

952 All global segments are considered and sorted by the criteria listed below in 2. Accumulation of
 953 Additional Segments and Stopping-Criteria. The best suitable segment from the beginning of that
 954 set of segments is used as the initial dataset for the network. Images are split into a training and
 955 a validation set (4:1 ratio). Efforts are made to equalize the sample sizes per class/identity before-
 956 hand, but there has to always be a trade-off between similar sample sizes (encouraging unbiased
 957 priors) and having as many samples as possible available for the network to learn from. Thus, in or-
 958 der to alleviate some of the severity of dealing with imbalanced datasets, the performance during
 959 training iterations is evaluated using a categorical focal loss function (*Lin et al., 2020*). Focal loss
 960 down-weights classes that are already reliably predicted by the network and in turn emphasizes ne-
 961 glected classes. An Adam optimizer (*Kingma and Ba, 2015*) is used to traverse the loss landscape
 962 towards the global (or to at least a local) minimum.

963 The network layout used for the classification in TRex (see *Figure 1c*) is a typical Convolutional
 964 Neural Network (CNN). The concepts of "convolutional" and "downsampling" layers, as well as the
 965 back-propagation used during training, are not new. They were introduced in *Fukushima (1988)*,
 966 inspired originally by the work of Hubel and Wiesel on cats and rhesus monkeys (*Hubel and Wiesel*
 967 *1959, Hubel and Wiesel 1963, Wiesel and Hubel 1966*), describing receptive fields and their hierar-
 968 chical structure in the visual cortex. Soon afterward, in *LeCun et al. (1989)*, CNNs, in combination
 969 with back-propagation, were already successfully used to recognize handwritten ZIP codes – for
 970 the first time, the learning process was fully automated. A critical step towards making their appli-
 971 cation practical, and the reason they are popular today.

972 The network architecture used in our software is similar to the identification module of the net-
 973 work in *Romero-Ferrero et al. (2019)*, and is, as in most typical CNNs, (reverse-)pyramid-like. How-

ever, key differences between TRex' and idtracker.ai's procedure lie with the way that training data is prepared (see previous sections) and how further segments are accumulated/evaluated (see next section). Furthermore, contrary to idtracker.ai's approach, images in TRex are augmented (during training) before being passed on to the network. While this augmentation is relatively simple (random shift of the image in x-direction), it can help to account for positional noise introduced by e.g. the posture estimation or the video itself when the network is used for predictions later on (*Perez and Wang, 2017*). We do not flip the image in this step, or rotate it, since this would defeat the purpose of using orientation normalization in the first place (as in Minimizing the Variance Landscape by Normalizing Samples, see *Figure 8*). Here, in fact, normalization of object orientation (during training and predictions) could be seen as a superior alternative to data augmentation.

The input data for TRex' network is a single, cropped grayscale image of an individual (see *Figure 1c*). This image is first passed through a "lambda" layer (blue) that normalizes the pixel values, dividing them by half the value limit of $255/2 = 127.5$ and subtracting 1 – this moves them into the range of $[-1, 1]$. From then on, sections are a combination of convolutional layers (kernel sizes of 16, 64 and 100 pixels), each followed by a 2D (2x2) max-pooling and a 2D spatial dropout layer (with a rate of 0.25). Within each of these blocks the input data is reduced further, focussing it down to information that is deemed important. Towards the end, the data are flattened and flow into a densely connected layer (100 units) with exactly as many outputs as the number of classes. The output is a vector with values between 0 and 1 for all elements of the vector, which, due to softmax-activation, sum to 1.

Training commences by performing a stochastic gradient descent (using the Adam optimizer, see *Kingma and Ba 2015*), which iteratively minimizes the error between network predictions and previously known associations of images with identities – the original assignments within the initial frame segment. The optimizer's behavior in the last five epochs is continuously observed and training is terminated immediately if one of the following criteria is met:

- 1000 • the maximum number of iterations is reached (150 by default, but can be set by the user)
- 1001 • a plateau is achieved at a high per-class accuracy
- 1002 • overfitting/overly optimizing for the training data at the loss of generality
- 1003 • no further improvements can be made (due to the accuracy within the current training data already being 1)

1005 The initial training unit is also by far the most important as it determines the predicted identities
 1006 within further segments that are to be added. It is thus less risky to overfit than it is important
 1007 to get high-quality training results, and the algorithm has to be relatively conservative regarding
 1008 termination criteria. Later iterations, however, are only meant to extend an already existing dataset
 1009 and thus (with computation speed in mind) allow for additional termination criteria to be added:

- 1010 • plateauing at/circling around a certain val_loss level
- 1011 • plateauing around a certain uniqueness level

1012 2. Accumulation of Additional Segments and Stopping-Criteria

1013 If necessary, initial training results can be improved by adding more samples to the active dataset.
 1014 This could be done manually by the user, always trying to select the most promising segment next,
 1015 but requiring such manual work is not acceptable for high-throughput processing. Instead, in order
 1016 to translate this idea into features that can be calculated automatically, the following set of metrics
 1017 is re-generated per (yet inactive) segment after each successful step:

- 1018 1. Average uniqueness index (rounded to an integer percentage in 5% steps)
- 1019 2. Minimal distance to regions that have previously been trained on (rounded to the next power
 1020 of two), larger is better as it potentially includes samples more different from the already
 1021 known ones

- 1022 3. Minimum *cells visited* per individual (larger is better for the same reason as 2)
 1023 4. Minimum average samples per individual (larger is better)
 1024 5. Whether its image data has already been generated before (mostly for saving memory)
 1025 6. The uniqueness value is smaller than U_{prev}^2 after 5 steps, with U_{prev} being the best uniqueness
 1026 value previous to the current accumulation step

1027 With the help of these values, the segment list is sorted and the best segment selected to be
 1028 considered next. Adding a segment to a set of already active samples requires us to correct the
 1029 identities inside it, potentially switching temporary identities to represent the same *real* identities
 1030 as in our previous data. This is done by predicting identities for the new samples using the network
 1031 that has been trained on the old samples. Making mistakes here can lead to significant subsequent
 1032 problems, so merely plausible segments will be added - meaning only those samples are accepted
 1033 for which the predicted IDs are *unique* within each unobstructed sequence of frames for every
 1034 temporary identity. If multiple temporary individuals are predicted to be the same real identity,
 1035 the segment is saved for later and the search continues.

1036 If multiple additional segments are found, the program tries to actively improve local uniqueness
 1037 valleys by adding samples first from regions with comparatively *low* accuracy predictions. Seeing
 1038 as low accuracy regions will also most likely fail to predict unique identities, it is important to
 1039 emphasize here that this is generally not a problem for the algorithm: Failed segments are sim-
 1040 ply ignored and can be inserted back into the queue later. Smoothing the curve also makes sure
 1041 to prefer regions close to valleys, making the algorithm follow the valley walls upwards in both
 1042 directions.

1043 Finishing a training unit does not necessarily mean that it was successful. Only the network
 1044 states improving upon results from previous units are considered and saved. Any training result -
 1045 except the initial one - may be rejected after training in case the uniqueness score has not improved
 1046 globally, or at least remained within 99% of the previous best value. This ensures stability of the
 1047 process, even with tracking errors present (which can be corrected for later on, see next section).
 1048 If a segment is rejected, the network is restored to the best recorded state.

1049 Each new segment is always combined with regularly sampled data from previous steps, en-
 1050 suring that identities don't switch back and forth between steps due to uncertain predictions. If
 1051 switching did occur, then the uniqueness and accuracy values can never reach high value regimes
 1052 - leading to the training unit being discarded as a result. The contribution of each previously added
 1053 segment R is limited to $\lceil |R_S| / (\text{samples_max} * |R| / N) \rceil$ samples, with N as the total number of frames
 1054 in global segments for this individual and samples_max a constant that is calculated using image size
 1055 and memory constraints (or 1GB by default). R_S is the actual *usable* number of images in segment
 1056 R . This limitation is an attempt to not bias the priors of the network by sub-sampling segments
 1057 according to their contribution to the total number of frames in global segments.

1058 Training is considered to be successful globally, as soon as either (i) accumulative individual
 1059 gaps between sampled regions is less than 25% of the video length for all individuals, or (ii) unique-
 1060 ness has reached a value higher than $1 - \frac{0.5}{N_{id}}$ (1) so that almost all detected identities are present
 1061 exactly once per frame. Otherwise, training will be continued as described above with additional
 1062 segments - each time extending the percentage of images seen by the network further.

1063 Training accuracy/consistency could potentially be further improved by letting the program add
 1064 an arbitrary amount of segments, however we found this not to be necessary in any of our test-
 1065 cases. Users are allowed to set a custom limit if required in their specific cases.

1066 3. The Final Training Unit

1067 After the accumulation phase, one last training step is performed. In previous steps, validation data
 1068 has been kept strictly separate from the training set to get a better gauge on how generalizable
 1069 the results are to unseen parts of the video. **This is especially important during early training units,**
 1070 **since "overfitting" is much more likely to occur in smaller datasets and we still potentially need to**

1071 add samples from different parts of the video. Now that we are not going to extend our training
 1072 dataset anymore, maintaining generalizability is no longer the main objective – so why not use *all* of
 1073 the available data? The entire dataset is simply merged and sub-sampled again, according to the
 1074 memory strategy used. Network training is started, with a maximum of $\max\{3; \text{max_epochs} * 0.25\}$
 1075 iterations (max_epochs is 150 by default). During this training, the same stopping-criteria apply as
 1076 during the initial step.

1077 Even if we tolerate the risk of potentially overfitting on the training data, there is still a way to
 1078 detect overfitting if it occurs: Only training steps that lead to improvements in mean uniqueness
 1079 across the video are saved. Often, if prediction results become worse (e.g. due to overfitting),
 1080 multiple individuals in a single frame are predicted to be the same identity – precisely the problem
 1081 which our uniqueness metric was designed to detect.

1082 For some videos, this is the step where most progress is made (e.g. video 9). The reason being
 1083 that this is the first time when all of the training data from all segments is considered at once
 1084 (instead of mostly the current segment plus fewer samples from previously accepted segments),
 1085 and samples from all parts of the video have an equal likelihood of being used in training after
 1086 possible reduction due to memory-constraints.

1087 4. Assigning Identities Based on Network Predictions

1088 After the network has been successfully trained, all parts of the video which were not part of the
 1089 training are packaged together and the network calculates predictive probabilities for each image
 1090 of each individual to be any of the available identities. The vectors returned by the network are
 1091 then averaged per consecutive segment per individual. The average probability vectors for all over-
 1092 lapping segments are weighed against each other – usually forcing assignment to the most likely
 1093 identity (ID) for each segment, given that no other segments have similar probabilities. When re-
 1094 ferring to segments here, meant is simply a number of consecutive frames of one individual that
 1095 the tracker is fairly sure does *not* contain any mix-ups. We implemented a way to detect tracking
 1096 mistakes, which is mentioned later.

1097 If an assignment is ambiguous, meaning that multiple segments $S_{j\dots M}$ overlapping in time have
 1098 the same maximum probability index $\arg \max_{i \in [0, N]} \{P(i | S_j)\}$ (for the segment to belong to a certain
 1099 identity i), a decision has to be made. Assignments are deferred if the ratio

$$R_{\max} = \max \left\{ \frac{P(i | S_j)}{P(i | S_k)}, \forall S_{j \neq k} \in \text{overlapping segments} \right\}$$

1100 between any two maximal probabilities is *larger than* 0.6 for said i (R_{\max} is inverted if it is greater
 1101 than 1). In such a case, we rely on the general purpose tracking algorithm to pick a sensible op-
 1102 tion – other identities might even be successfully assigned (using network predictions) in following
 1103 frames, which is a complexity we do not have to deal with here. In case all ratios are *below* 0.6,
 1104 when the best choices per identity are not too ambiguous, the following steps are performed to
 1105 resolve remaining conflicts:

- 1106 1. count the number of samples N_{me} in the current segment, and the number of samples N_{he} in
 1107 the other segment that this segment is compared to
- 1108 2. calculate average probability vectors P_{me} and P_{he}
- 1109 3. if $S(P_{me}, N_{me}) \geq S(P_{he}, N_{he})$, then assign the current segment with the ID in question. Otherwise
 1110 assign the ID to the other segment. Where:

$$\begin{aligned} \text{norm}(x) &= \frac{x}{N_{me} + N_{he}}, \quad \text{sig}(x) = (1 + e^{2\pi(0.5-x)})^{-1} \\ S(p, x) &= \text{sig}(p) + \text{sig}(\text{norm}(x)). \end{aligned} \tag{2}$$

1111 This procedure prefers segments with larger numbers of samples over segments with fewer
 1112 samples, ensuring that identities are not switched around randomly whenever a short segment
 1113 (e.g. of noisy data) is predicted to be the given identity for a few frames – at least as long as a

1114 better alternative is available. The non-linearity in $S(p, x)$ exaggerates differences between lower
 1115 values and dampens differences between higher values: For example, the quality of a segment
 1116 with 4000 samples is barely different from a segment with 5000 samples; however, there is likely to
 1117 be a significant quality difference between segments with 10 and 100 samples.

1118 In case something goes wrong during the tracking, e.g. an individual is switched with another
 1119 individual without the program knowing that it might have happened, the training might still be
 1120 successful (for example if that particular segment has not been used for training). In such cases,
 1121 the program tries to correct for identity switches mid-segment by calculating a running-window
 1122 median identity throughout the whole segment. If the identity switches for a significant length of
 1123 time, before identities are assigned to segments, the segment is split up at the point of the first
 1124 change within the window and the two parts are handled as separate segments from then on.

1125 Software and Licenses

1126 TRex is published under the GNU GPLv3 license (see [here](#) for permissions granted by GPLv3). All of
 1127 the code has been written by the first author of this paper (a few individual lines of code from other
 1128 sources have been marked inside the code). While none of these libraries are distributed alongside
 1129 TRex (they have to be provided separately), the following libraries are used: OpenCV ([opencv.org](#))
 1130 is a core library, used for all kinds of image manipulation. GLFW ([glfw.org](#)) helps with opening applica-
 1131 tion windows and maintaining graphics contexts, while DearImGui ([github.com/ocornut/imgui](#))
 1132 helps with some more abstractions regarding graphics. pybind11 ([Jakob et al. \(2017\)](#)) for Python
 1133 integration within a C++ environment. miniLZO ([oberhumer.com/opensource/lzo](#)) is used for com-
 1134 pression of PV frames. Optional bindings are available to FFmpeg ([ffmpeg.org](#)) and libpng libraries,
 1135 if available. (optional) GNU Libmicrohttpd ([gnu.org/software/libmicrohttpd](#)), if available, can be
 1136 used for an HTTP interface of the software, but is non-essential.

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- 1362 puter Graphics and Interactive Techniques; 1978. p. 270–274. doi: <https://doi.org/10.1145/800248.807402>.

1363 **Appendix 1**

1364 **Installation requirements and Usage**

1365 Compiled, ready-to-use binaries are available for all major operating systems (Windows, Linux,
 1366 MacOS). However, it should be possible to compile the software yourself for any Unix- or
 1367 Windows-based system (≥ 8), possibly with minor adjustments. Tested setups include:

- 1368 • Windows, Linux, MacOS
- 1369 • A computer with $\geq 16\text{GB}$ RAM is recommended
- 1370 • OpenCV^a libraries $\geq \text{v}3.3$
- 1371 • Python libraries $\geq \text{v}3.6$, as well as additional packages such as:
- 1372 • Keras $\approx \text{v}2.2$ with one of the following backends installed
 - 1373 – Tensorflow $< \text{v}2^b$ (either CPU-based, or GPU-based)
 - 1374 – Theano^c
- 1375 • GPU-based recognition requires an NVIDIA graphics-card and drivers (see Tensorflow
 1376 documentation)

1377 For detailed download/installation instructions and up-to-date requirements, please refer
 1378 to the documentation at trex.run/install.

1379 **Workflow**

1380 TRex can be opened in one of two ways: (i) Simply starting the application (e.g. using the
 1381 operating systems' file-browser), (ii) using the command-line. If the user simply opens the
 1382 application, a file opening dialog displays a list of compatible files as well as information on
 1383 a selected files content. Certain startup parameters can be adjusted from within the graph-
 1384 ical user-interface, before confirming and loading up the file (see **Appendix 1 Figure A2**).
 1385 Users with more command-line experience, or the intent of running TRex in batch-mode,
 1386 can append necessary parameter values without adding them to a settings file.

1387 To acquire video-files that can be opened using TRex, one needs to first run TGabs in
 1388 one way or another. It is possible to use a webcam (generic USB camera) for recording, but
 1389 TGabs can also be compiled with Basler Pylon5 support^d. TGabs can also convert existing
 1390 videos and write to a more suitable format for TRex to interact with (a static background
 1391 with moving objects clearly separated in front of it). It can be started just like TRex, although
 1392 most options are either set via the command-line, or a web-interface. TGabs can perform
 1393 basic tracking tasks on the fly, offering closed-loop support as well.

1394 For automatic visual recognition, one might need to adjust some parameters. Mostly,
 1395 these adjustments consist of changing the following parameters:

- 1396 • `blob_size_ranges`: Setting one (or multiple) size thresholds for individuals, by giving
 lower and upper limit value pairs.
- 1397 • `track_max_individuals`: Sets the number of individuals expected in a trial. This num-
 ber needs to be known for recognition tasks (and will be guessed if not provided), but
 can be set to 0 for unknown numbers of individuals.
- 1398 • `track_max_speed`: Sets the maximum speed (cm/s) that individuals are expected to
 travel at. This is influenced by meta information provided to TGabs by the user (e.g.
 the width of the tank), as well as frame timings.
- 1399 • `track_threshold`: Even TRex can threshold images of individuals, so it is beneficial to
 not threshold away too many pixels during conversion/recording and do finer-grade
 adjustments in the tracker itself.

- 1407 • **outline_resample**: A factor that is > 0 , by which the number of points in the outline is
 1408 essentially "divided". Smaller resample rates lead to more points on the outline (good
 1409 for very small shapes).

1410 Training can be started once the user is satisfied with the basic tracking results. Consec-
 1411 utive segments are highlighted in the time-line and suggest better or worse tracking, based
 1412 on their quantity and length. Problematic segments of the video are highlighted using yel-
 1413 low bars in that same time-line, giving another hint to the user as to the tracking quality. To
 1414 start the training, the user just clicks on "train network" in the main menu – triggering the
 1415 accumulation process immediately. After training, the user can click on "auto correct" in the
 1416 menu and let TRex correct the tracks automatically (this will re-track the video). The entire
 1417 process can be automated by adding the "auto_train" parameter to the command-line, or
 1418 selecting it in the interface.

1419 **Output**

1420 Once finished, the user may export the data in the desired format. Which parts of the data
 1421 are exported is up to the user as well. By default, almost all the data is exported and saved
 1422 in NPZ files in the output folder.

1423 Output folders are structured in this way:

- 1424 • **output** folder:
 - 1425 – Settings files
 - 1426 – Training weights
 - 1427 – Saved program states
 - 1428 – **data** folder:
 - 1429 * Statistics
 - 1430 * All exported NPZ files (named [video_name]_fish[number].npz – the prefix
 "fish" can be changed).
 - 1431 * ...
 - 1432 – **frames** folder (contains video clips recorded in the GUI, e.g. for presentations):
 - 1433 * [video name] folder
 - 1434 · clip[index].avi
 - 1435 · ...
 - 1436 * ...

1438 At any point in time (except during training), the user can save the current program state
 1439 and return to it at a later time (e.g. after a computer restart).

1440 Export options

1441 After individuals have been assigned by the matching algorithm, various metrics are calcu-
 1442 lated (depending on settings):

- 1443 • **Angle**: The angle of an individual can be calculated without any context using image
 moments ([Hu \(1962\)](#)). However, this angle is only reliable within 0 to 180 degrees – not
 the full 360. Within these 180 degrees it is probably more accurate than is movement
 direction.
- 1444 • **Position**: Centroid information on the current, as well as the previous position of the
 individual are maintained. Based on previous positions, velocity as well as acceleration
 are calculated. This process is based on information sourced from the respective video
 file or camera on the time passed between frames. The centroid of an individual is

calculated based on the mass center of the pixels that the object comprises. Angles calculated in the previous steps are corrected (flipped by 180 degrees) if the angle difference between movement direction and angle + 180 degrees is smaller than with the raw angle.

- **Posture:** A large part of the computational complexity comes from calculating the posture of individuals. While this process is relatively fast in TRex, it is still the main factor (except with many individuals, where the matching process takes longest). We dedicated a subsection to it below.
- **Visual Field:** Based on posture, rays can be cast to detect which animal is visible from the position of another individual. We also dedicated a subsection to visual field further down.
- **Other** features can be computed, such as inter-individual distances or distance to the tank border. These are optional and will only be computed if necessary when exporting the data. A (non-comprehensive) list of metrics that can be exported follows:
 - Time: The time of the current frame (relative to the start of the video) in seconds.
 - Frame: Index of the frame in the PV video file.
 - Individual components of position its derivatives (as well as their magnitudes, e.g. speed)
 - Midline offset: The center-line, e.g. of a beating fish-tail, is normalized to be roughly parallel to the x-axis (from its head to a user-defined percentage of a body). The y-offset of its last point is exported as a "midline offset". This is useful, e.g. to detect burst-and-glide events.
 - Midline variance: Variance in midline offset, e.g. for detection of irregular postures or increased activity.
 - Border distance
 - Average neighbour distance: Could be used to detect individuals who prefer to be located far away from the others or are avoided by them.

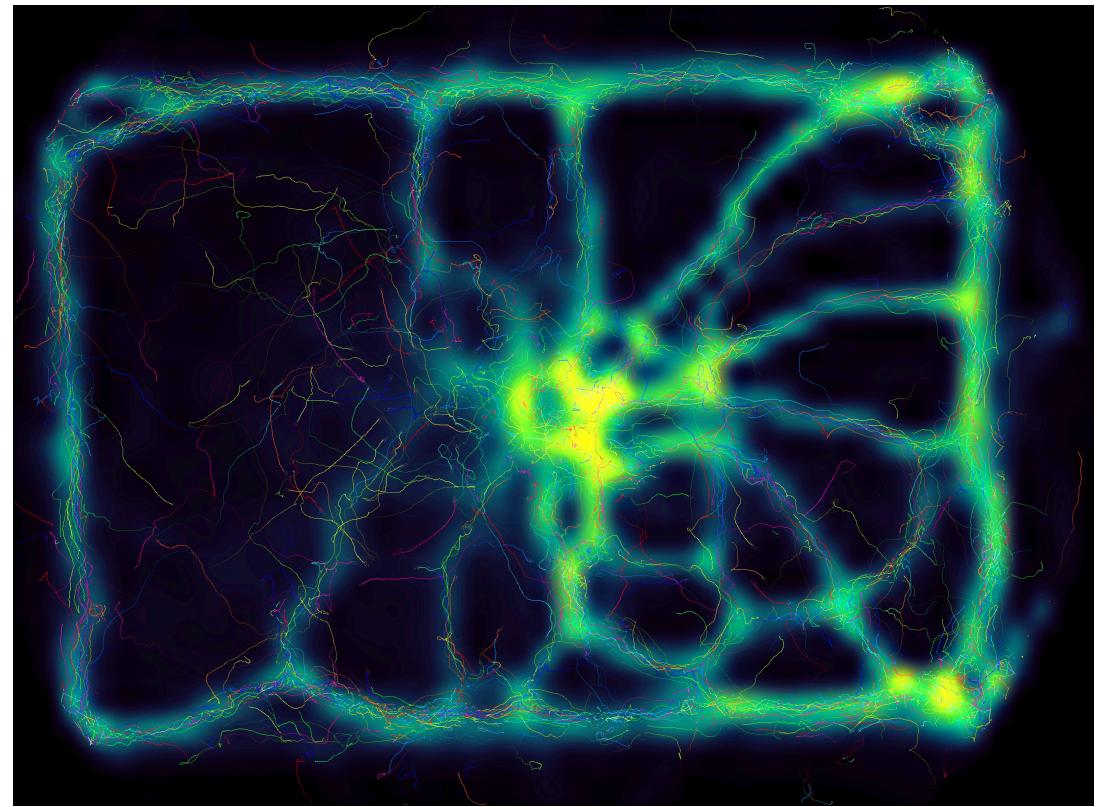
Additionally, tracks of individuals can be exported as a series of cropped-out images – a very useful tool if they are to be used with an external posture estimator or tag-recognition. This series of images can be either every single image, or the median of multiple images (the time-series is down-sampled).

^aopencv.org

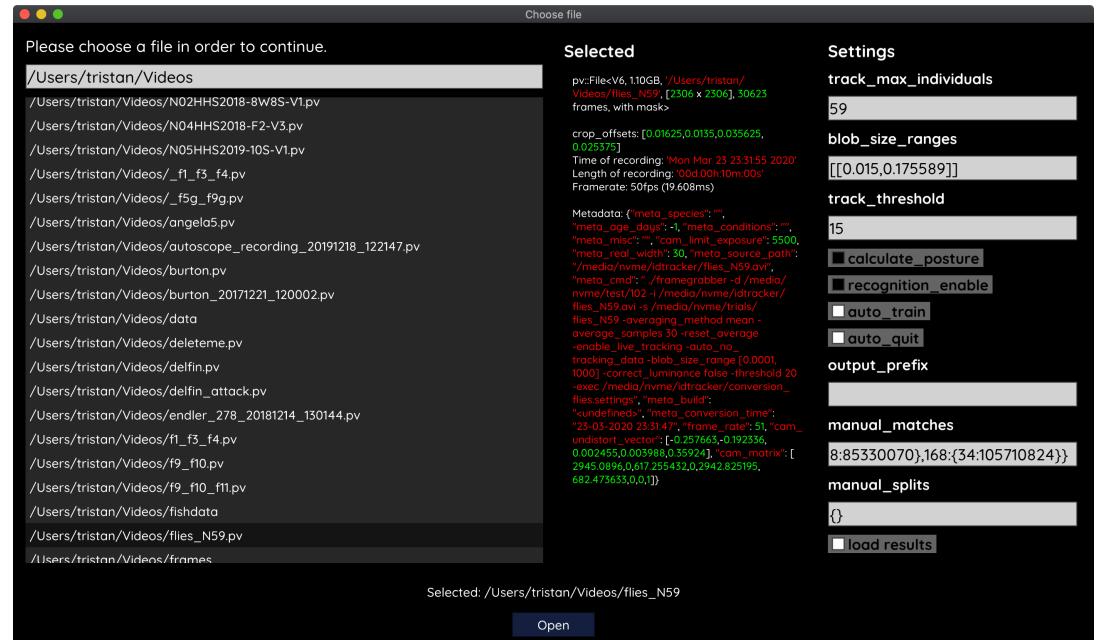
^btensorflow.org

^cdeeplearning.net

^dThe baslerweb.com Pylon SDK is required to be installed to support Basler USB cameras.



Appendix 1 Figure A1. Using the interactive heatmap generator within TRex, the foraging trail formation of *Constrictotermes cyphergaster* (termites) can be visualized during analysis, as well as other potentially interesting metrics (based on posture- as well basic positional data). This is generalizable to all output data fields available in TRex, e.g. also making it possible to visualize "time" as a heatmap and showing where individuals were more likely to be located during the beginning or towards end of the video. Video: H. Hugo



Appendix 1 Figure A2. The file opening dialog. On the left is a list of compatible files in the current folder. The center column shows meta-information provided by the video file, including its frame-rate and resolution – or some of the settings used during conversion and the timestamp of conversion. The column on the right provides an easy interface for adjusting the most important parameters before starting up the software. Most parameters can be changed later on from within TRex as well.

1482 Appendix 2

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1484 **From video frame to blobs**

1485 Video frames can originate either from a camera, or from a pre-recorded video file saved
 1486 on disk. `TGrabs` treats both sources equally, the only exception being some minor details
 1487 and that pre-recorded videos have a well-defined end (which only has an impact on MP4
 1488 encoding). Multiple formats are supported, but the full list of supported codecs depends
 1489 on the specific system and OpenCV version installed. `TGrabs` saves images in RAW quality,
 1490 but does not store complete images. Merely the objects of interest, defined by common
 1491 tracking parameters such as size, will actually be written to a file. Since `TGrabs` is mostly
 1492 meant for use with stable backgrounds (except when contrast is good or a video-mask is
 1493 provided), the rest of the area can be approximated by a static background image generated
 1494 in the beginning of the process (or previously).

1495 Generally, every image goes through a number of steps before it can be tracked in `TRex`:

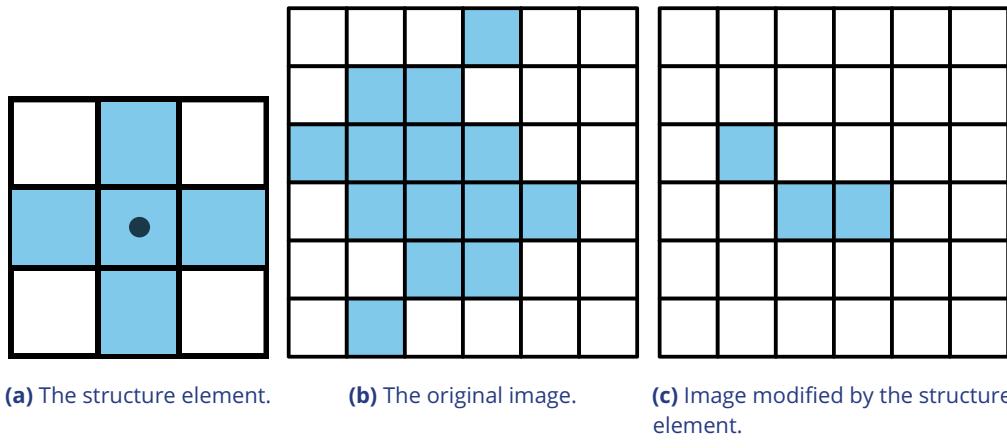
- 1496 1. Images are decoded by either (i) a camera driver, or (ii) OpenCV. They consist of an
 array of values between 0 and 255 (grayscale). Color images will be converted to
 grayscale images (color channel or "hue" can be chosen).
- 1497 2. Timing information is saved and images are appended to a queue of images to be
 processed
- 1498 3. All operations from now on are performed on the GPU if available. Once images are
 in the queue, they are picked one-by-one by the processing thread, which performs
 operations on them based on user-defined parameters:
 - 1499 • Cropping
 - 1500 • Inverting
 - 1501 • Contrast/brightness and lighting corrections
 - 1502 • Undistortion (see OpenCV [Tutorial](#))
- 1503 4. (optional) Background subtraction ($d(x) = b(x) - f(x)$, with f being the image and b the
 background image), leaving a difference image containing only the objects. This can
 be an absolute difference $|b(x) - f(x)|$ or a signed one, which has different effects on
 the following step. Otherwise $d(x) = f(x)$
- 1504 5. Thresholding to obtain a binary image, with all pixels either being 1 or 0:

$$t(x) = \begin{cases} 0 & d(x) < T \\ 1 & d(x) \geq T \end{cases}$$

1505 where $0 \leq T \leq 255$ is the threshold constant.

- 1506 6. Options are available for further adjustment of the binary image: Dilation, Erosion and
 Closing are used to close gaps in the shapes, which are filled up by successive dilation
 and erosion operations (see [Appendix 2 Figure A1](#)). If there is an imbalance of dilation
 and erosion commands, noise can be removed or shapes made more inclusive.
- 1507 7. The original image is multiplied by the thresholded image, obtaining a masked grayscale
 image: $t(x) \cdot f(x)$, where \cdot is the element-wise multiplication operator.

1508 At this point, the masked image is returned to the CPU, where connected components
 1509 (objects) are detected. A connected component is a number of adjacent pixels with color
 1510 values greater than zero. Algorithms for connected-component labeling either use a 4-
 1511 neighborhood or an 8-neighborhood, which considers diagonal neighbors to be adjacent
 1512 as well. Many such algorithms are available ([AbuBaker et al. \(2007\)](#), [Chang and Chen \(2003\)](#),



Appendix 2 Figure A1. Example of morphological operations on images: "Erosion". Blue pixels denote on-pixels with color values greater than zero, white pixels are "off-pixels" with a value equal to zero. A mask is moved across the original image, with its center (dot) being the focal pixel. A focal pixel is *retained* if all of the on-pixels within the structure element/mask are on top of on-pixels in the original image. Otherwise the focal pixel is set to 0. The type of operation performed is entirely determined by the structure element.

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and many others), even capable of real-time speeds (**Suzuki et al. (2003)**, **He et al. (2009)**). However, since we want to use a compressed representation throughout our solution, as well as transfer over valuable information to integrate it with posture analysis, we needed to implement our own (see Connected components algorithm).

MP4 encoding has some special properties, since its speed is mainly determined by the external encoding software. Encoding at high-speed frame-rates can be challenging, since we are also encoding to a PV-file simultaneously. Videos are encoded in a separate thread, without muxing, and will be remuxed after the recording is stopped. For very high frame-rates or resolutions, it may be necessary to limit the duration of videos since all of the images have to be kept in RAM until they have been encoded. RAW images in RAM can take up a lot of space ($1024 * 1024 * 1000 = 1,048,576,000$ bytes for 1000 images quite low in resolution). If there a recording length is defined prior to starting the program, or a video is converted to PV and streamed to MP4 at the same time (though it is unclear why that would be necessary), TGrabs is able to automatically determine which frame-rate can be maintained reliably and without filling the memory.

1542 Appendix 3

1543
1544 **Connected components algorithm**

1545 Pixels are not represented individually in TRex. Instead, they are saved as connected horizontal line segments. For each of these lines, only y- as well as start- and end-position are 1546 saved (y, x_0 and x_1). This representation is especially suited for objects stretching out along 1547 the x-axis, but of course its worst-case is a straight, vertical line – in which case space 1548 requirements are $O(2 * N)$ for N pixels. Especially for big objects, however, only a fraction 1549 of coordinates has to be kept in memory (with a space requirement of $O(2 * H)$ instead of 1550 $O(W * H)$, with W, H being width and height of the object).

1551 Extracting these connected horizontal line segments from an image can be parallelized 1552 easily by cutting the image into full-width pieces and running the following algorithm 1553 repeatedly for each row:

- 1554 1. From 0 to W , iterate all pixels. Always maintain the previous value (binary), as well 1555 as the current value. We start out with our previous value of $\bar{p} = 0$ (the border is 1556 considered not to be an object).
- 1557 2. Now repeat for every pixel p_i in the current row:
 - 1558 (a) If \bar{p} is 1 and p_i is 0, set $\bar{p} := 0$ and save the position as the end of a line segment 1559 $x_1 = i - 1$.
 - 1560 (b) If \bar{p} is 0 and p_i is 1, we did not have a previous line segment and a new one starts. 1561 We save it as our current line segment with x_0 and y equal to the current row. Set 1562 $\bar{p} := 1$.
- 1563 3. After each row, if we have a valid current line, we save it in our array of lines. If $\bar{p} = 1$ 1564 was set, and the line segment ended at the border W of the image, we first set its end 1565 position to $x_1 := W - 1$.

1566 We keep the array of extracted lines sorted by their y-coordinate, as well as their x- 1567 coordinates in the order we encountered them. To extract connected components, we now 1568 just need to walk through all extracted rows and detect changes in the y-coordinate. The 1569 only information needed are the current row and the previous row, as well as a list of active 1570 preliminary "blobs" (or connected components). A blob is simply a collection of ordered 1571 horizontal line segments belonging to a single connected component. These blobs are 1572 preliminary until the whole image has been processed, since they might be merged into a single 1573 blob further down despite currently being separate (see *Appendix 3 Figure A1*).

1574 "Rows" are an array of horizontal lines with the same y-coordinate, ordered by their x- 1575 coordinates (increasing). The following algorithm only considers pairs of previous row R_{i-1} 1576 and current row R_i . We start by inserting all separate horizontal line segments of the 1577 very first row into the pool of active blobs, each assigned their own blob. Lines within row R_i 1578 are $L_{i,j}$. Coordinates of $L_{i,j}$ will be denoted as $x_0(i, j)$, $x_1(i, j)$ and $y(i, j)$. Our current index 1579 in row R_{i-1} is j and our index in row R_i is k . We initialize $j := 0, k := 1$. Now for each pair 1580 of rows, three different actions may be required depending on the case at hand. All three 1581 actions are hierarchically ordered and mutually exclusive (like a typical `if/else` structure 1582 would be), meaning that case 0-2 can be true at the same time while no other combination 1583 can be simultaneously true:

1. **Case 0, 1 and 2: We have to create a new blob.** This is the case if (0) the line in R_i ends before the line in R_{i-1} starts ($x_1(i, k) + 1 < x_0(i, j)$), or (1) y-coordinates of R_i and

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R_{i-1} are farther apart than 1 ($y(i-1, j) > y(i, k) + 1$), or (2) there are no lines left in R_{i-1} to match the current line in R_i to ($j \geq |R_{i-1}|$). $L_{i,k}$ is assigned with a new blob.

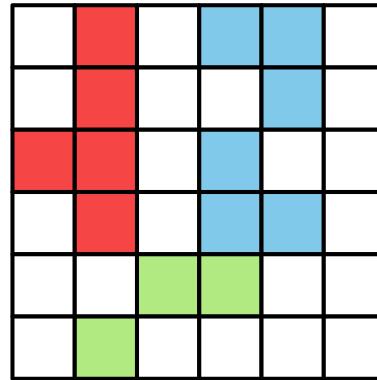
2. **Case 3: Segment in the previous row ends before the segment in the current row starts.** If $x_0(i, k) > x_1(i-1, j) + 1$, then we just have to $j := j + 1$.

3. **Case 4: Segment in the previous row and segment in the current row intersect in x-coordinates.** If $L_{i,k}$ is no yet assigned with a blob, assign it with the one from $L_{i-1,j}$. Otherwise, both blobs have to be merged. This is done in a sub-routine, which guarantees that lines within blobs stay properly sorted during merging. This means that (i) y-coordinates increase or stay the same and (ii) x-coordinates increase monotonically. Afterwards, we increase either k or j based on which one associated line ends earlier: If $x_1(i, k) \leq x_1(i-1, j)$, then we increase $k := k + 1$; otherwise $j := j + 1$.

After the previous algorithm has been executed on a pair of R_{i-1} and R_i , we increase i by one $i := i+1$. This process is continued until $i = H$, at which point all connected components are contained within the active blob array.

Retaining information about pixel values adds slightly more complexity to the algorithm, but is straight-forward to implement. In TRex, horizontal line segments comprise y , x_0 and x_1 values plus an additional pointer. It points to the start of a line within array of all pixels (or an image matrix), adding only little computational complexity overall.

Based on the horizontal line segments and their order, posture analysis can be sped up when properly integrated. Another advantage is that detection of connected components within arrays of horizontal line segments is supported due to the way the algorithm functions – we can just get rid of the extraction phase.



Appendix 3 Figure A1. An example array of pixels, or image, to be processed by the connected components algorithm. This figure should be read from top to bottom, just as the connected components algorithm would do. When this image is analysed, the red and blue objects will temporarily stay separate within different "blobs". When the green pixels are reached, both objects are combined into one identity.

1608 Appendix 4

1609 **Matching an object to an object in the next frame**1610 **Terminology**

1611 A graph is a mathematical structure commonly used in many fields of research, such as
 1612 computer science, biology and linguistics. Graphs are made up of vertices, which in turn
 1613 are connected by edges. Below we define relevant terms that we are going to use in the
 1614 following section:

- 1615 • Directed graph: Edges have a direction assigned to them
- 1616 • Weighted edges: Edges have a weight (or cost) assigned to them
- 1617 • Adjacent nodes: Nodes which are connected immediately by an edge
- 1618 • Path: A path is a sequence of edges, where each edges starting vertex is the end vertex
 of the previous edge
- 1619 • Acyclic graph: The graph contains no path in which the same vertex appears more
 than once
- 1620 • Connected graph: There are no vertices without edges, there is a path from any vertex
 to any other vertex in the graph
- 1621 • Bipartite graph: Vertices can be sorted into two distinct groups, without an edge from
 any vertex to elements of its own group – only to the other group
- 1622 • Tree: A tree is a connected, undirected, acyclic graph, in which any two vertices are
 only connected by exactly one path
- 1623 • Rooted, directed out-tree: A tree where one vertex has been defined to be the root
 and directed edges, with all edges flowing away from the root
- 1624 • Visited vertex: A vertex that is already part of the current path
- 1625 • Leaf: A vertex which has only one edge arriving, but none going out (in a tree this are
 the bottom-most vertices)
- 1626 • Depth-first/breadth-first and best-first search: Different strategies to pick the next ver-
 tex to explore for a set of paths with traversable edges. Depth-first prefers to first go
 deeper inside a graph/tree, before going on to explore other edges of the same ver-
 tex. Breadth-first is the opposite of depth-search. Best-first search uses strategies to
 explore the most promising path first.

1638 **Background**

1639 The transportation problem is one of the fundamental problems in computer science. It
 1640 solves the problem of transporting a finite number of *goods* to a finite number of *factories*,
 1641 where each possible transport route is associated with a *cost* (or weight). Every factory has
 1642 a *demand* for goods and every good has a limited *supply*. The sum of this cost has to be
 1643 minimized (or benefits maximized), while remaining within the constraints given by supply
 1644 and demand. In the special case where demand by each factory and supply for each good
 1645 are exactly equal to 1, this problem reduces to the *assignment problem*.

The assignment problem can be further separated into two distinct cases: the *balanced* and the *unbalanced* assignment problem. In the balanced case, net-supply and demand are the same – meaning that the number of factories matches exactly the number of suppliers. While the balanced case can be solved slightly more efficiently, most practical problems are usually unbalanced ([Ramshaw and Tarjan \(2012\)](#)). Thankfully, unbalanced assignments can be reduced to balanced assignments, for example using graph-duplication methods or by adding nodes ([Ramshaw and Tarjan \(2012\)](#), [Ramshaw and Tarjan \(2012\)](#)). This makes the widely used Hungarian method ([Kuhn \(1955\)](#); [Munkres \(1957\)](#)) a viable solution to both,

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with a computational complexity of $O(n^3)$. It can be further improved using Fibonacci heaps (not implemented in TReX), resulting in $O(ms + s^2 \log n)$ time-complexity (**Fredman and Tarjan (1987)**), with m being the number of possible connections/edges, $s \leq n$ the number of factories to be supplied and n the number of factories. Re-balancing, by adding nodes or other structures, also adds computational cost – especially when $s \ll n$ (**Ramshaw and Tarjan (2012)**).

Adaptation for our matching problem

Assigning individuals to objects in the frame is, in the worst case, exactly that: an unbalanced assignment problem – potentially with $r \neq s$. During development, we found that we can achieve better average-complexity by combining an approach commonly used to solve *NP-hard* problems. This is a class problems for which it is (probably) not possible to find a polynomial-time solution. In order to motivate our usage of a less stable algorithm than e.g. the Hungarian method, let us first introduce a more general algorithm, following along with remarks for adapting it to our special case. The next subsection concludes with considerations regarding its complexity in comparison to the more stable Hungarian method.

Branch & Bound (or BnB, **Land and Doig (2010)**, formalized in **Little et al. (1963)**) is a very general approach to traversing the large search spaces of *NP-hard* problems, traditionally represented by a tree. Branching and bounding gives optimal solutions by traversing the entire search space if necessary, but stopping along the way to evaluate its options, always trying to choose better branches of the tree to explore next or skip unnecessary ones. BnB always consists of three main ingredients:

1. Branching: The division of our problem into smaller, partial problems
2. Bounding: Estimate the upper/lower limits of the probability/cost gain to be expected by traversing a given edge
3. Selection: Determining the next node to be processed

Finding good strategies is essential and can have a big impact on overall computation time. Strategies can only be worked out with insight into the specific problem, but *bounding* is generally the dominating factor here – in that choosing good selection and branching techniques cannot make up for a bad bounding function (**Clausen (1999)**). A bounding function estimates an upper (or lower) limit for the quality of results that can be achieved within a given sub-problem (current branch of the tree).

The "problem" is the entire assignment problem located at the root node of the tree. The further down we go in the tree, the smaller the partial problems become until we reach a leaf. Any graph can be represented as a tree by duplicating nodes when necessary (**Weixiong (1996)**, "Graph vs. tree"). So even if the bipartite assignment graph (an example sketched in **Appendix 4 Figure A1**) is a more "traditional" representation of the assignment problem, we can translate it into a rooted, directed out-tree $T = (U, V, E, F)$ with weighted edges. Here, U are individuals and V are objects in the current frame that are potentially assigned to identities in U . E are edges mapping from $U \rightarrow V$, while $F : V \rightarrow U$. It is quite visible from **Appendix 4 Figure A1**, that the representation as a tree (b) is much more verbose than a bipartite graph (a). However, its structure is very simple:

Looking at the tree in **Appendix 4 Figure A1** (b), individuals (blue) are found along the y-axis/deeper into the tree while objects in the frame (orange) are listed along on the x-axis. This includes a "null" case per individual, representing the possibility that it is *not* assigned to any object – ensuring that every individual has at least one edge.

Tree is never generated in its entirety (except in extreme cases), but it represents all *possible* combinations of individuals and objects. Overall, the set Q of every complete and valid path from top to bottom would be exactly the same as the set of every valid permutation

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of pairings between objects (plus null) and individuals. Edge weights in E are equal to the probability $P_i(t, \tau_i \mid B_j)$ (see equation 7), abbreviated to $P_i(B_j)$ here since we are only ever looking at one time-step. B_j is an object and i is an individual, so we can rewrite it in the current context as $P_u(v)$, with $u \in U; v \in V$.

We are maximizing the objective function

$$o(\rho) = \sum_{uv \in \rho} P_u(v),$$

where $\rho \in Q$ is an element of all valid paths within T .

The simplest approach would be to traverse every edge in the graph and accumulate a sum of probabilities along each path, guaranteeing to find the optimal solution eventually. Since the number of possible combinations $|U|^{|E|}$ grows rapidly with the number of edges, this is not realistic – even with few individuals. Thus, at least the *typical* number of visited edges has to be minimized. While we do not know the exact solution to our problem before traversing the graph, we can make very good guesses. For example, we may order nodes in such a way that branching (visiting a node leads to > 1 new edges to be visited) is reduced in most cases. To do that, we first need to calculate the *degree* of each individual. The degree C_u of individual u , which is exactly equivalent to the maximum number of edges going out from that individual, we define as

$$C_u \in \mathbb{N} := \sum_{u \in U} \begin{cases} 1 & \text{if } P_u(v) > P_{\min} \\ 0 & \text{otherwise} \end{cases}.$$

The maximally probable edge per individual also has to be computed beforehand, defined as

$$\overline{P}_u = \max_{v \in V} \{P_u(v)\}.$$

Nodes are sorted first by their degree (ascending) and secondly by \overline{P}_u (descending). We call this ordered set S . Sorting by degree ensures that the nodes with the fewest outgoing edges are visited *first*, causing severe branching to only happen in the lower regions of the tree. This is preferable, because a new branch in the bottom layer merely results in a few more options. If this happens at the top, the tree is essentially duplicated C_u times – in one step drastically increasing the overall number of items to be kept in memory. This process is, fittingly, called *node sorting* (**Weixiong (1996)**). Sorting by \overline{P}_u is only applied whenever nodes of the same degree have to be considered.

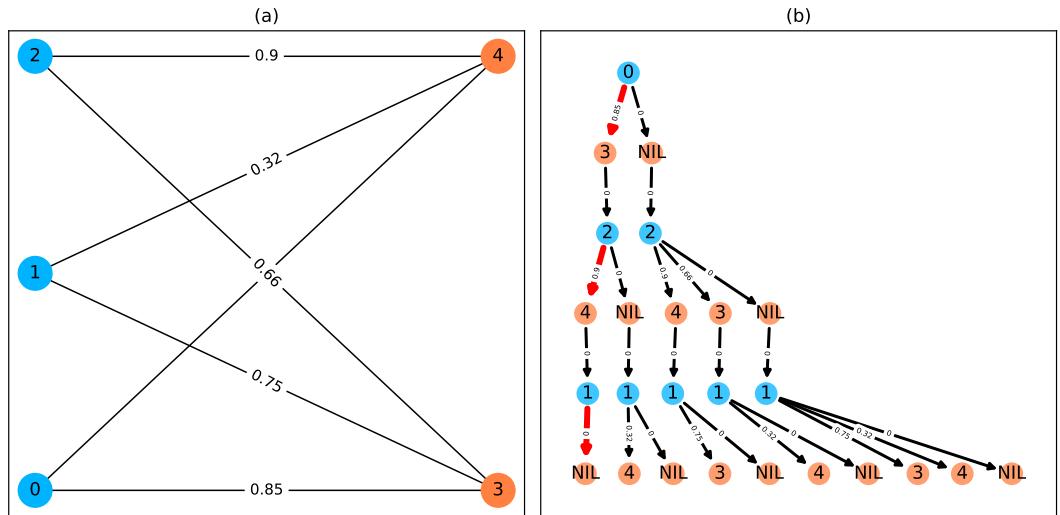
We always follow the most promising paths first (the one with the highest accumulated probability), which is called "best-first search" (BFS) – our selection strategy for (1.) in 4. BFS is implemented using a queue maintaining the list of all currently expanded nodes.

Regarding (2.) in 4, we utilize \overline{P}_u as an approximation for the upper bound to the achievable probability in each vertex. For each layer with vertices of U , we calculate an accumulative sum $\text{upper_limit}(i) = \sum_{j > i \in U} \overline{P}_j$, with j, i being indices into our ordered set S of individuals and i being the current depth in the graph (only counting vertices of U). This hierarchical upper limit for the expected value does not consider whether the respective edges are still *viable*, so they could have been eliminated already by assigning the object of V to another vertex of U above the current one. Any edge with $P_{\text{current}} + \text{upper_limit}(i) < P_{\text{best}}$ is skipped since it can not improve upon our previous best value P_{best} . If we do find an edge with a better value, we replace P_{best} with the new value and continue.

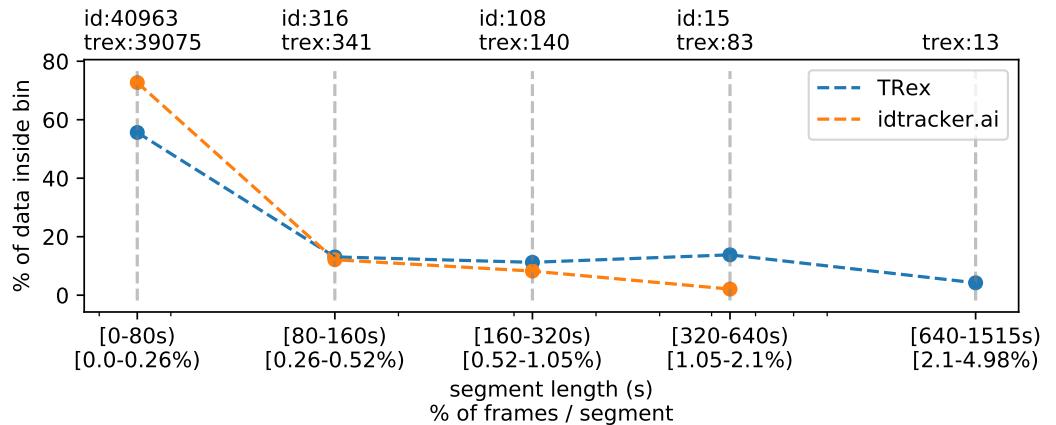
As an example, let us traverse the tree in **Appendix 4 Figure A1b**:

- 1753 • We first calculate \overline{P}_u for every $u \in U$ ($\overline{P}_0 = 0.85$; $\overline{P}_2 = 0.9$; $\overline{P}_1 = 0.75$), as well as the
 1754 hierarchical probability table `upper_limit(i)` for each index $0 \leq i < N$ ($0.9 + 0.75$; 0.75 ; 0).
 1755 $P_{\text{best}} := 0$.
 1756 • Individual 0 (the root) is expanded, which has one edge with probability $0.85 + \text{upper_limit}(0) \geq$
 1757 P_{best} to object 3 (plus the `null` case) and is the only node with a degree of 1. We know
 1758 that our now expanded node is the best, since it has the largest probability due to
 1759 sorting, plus also is the deepest. In fact, this is true for all expanded nodes exactly in
 1760 the order they are expanded (depth-first search == best-first search for our case). We
 1761 set $P_{\text{best}} := 0.85$. The edge to `NIL` is added to our queue.
 1762 • Objects in V are only virtual and always have zero-probability connections to the next
 1763 individual in an ordered set ($f \in F$), so they do not add to the overall probability sum.
 1764 We skip to the next node.
 1765 • Individual 2 branches off into one or two different edges, depending on which edges
 1766 have been chosen previously.
 1767 • We first explore the edge towards object 4 with a probability of $0.9 + \text{upper_limit}(1) =$
 1768 $1.65 \geq P_{\text{best}}$ and add it to P_{best} .
 1769 • Only one possibility is left and we arrive at a leaf with an accumulated probability of
 1770 $0.85 + 0.9 + 0 = 1.75$.
 1771 • We now perform backtracking, meaning we look at every expanded node in our queue,
 1772 each time observing $\overline{P}_u + \text{upper_limit}(i)$.
 1773 – `NIL` (from node 2) would be added to the front of our queue, however its proba-
 1774 bility $0.85 + 0 + \text{upper_limit}(1) = 1.6 < 1.75 = P_{\text{best}}$, so it is discarded.
 1775 – `NIL` (from node 0) would be added now, but its probability of $0 + \text{upper_limit}(0) =$
 1776 $1.65 < P_{\text{best}}$, so it is also discarded.
- 1777 We can see that with increased depth, we have to keep track of more and more pos-
 1778 sibilities. Since our nodes and edges are pre-sorted, our path through the tree is optimal
 1779 after exactly $N = |U|$ node expansions (not counting $v \in V$ expansions since they are only
 1780 "virtual").
- 1781 Complexity
- 1782 Utilizing these techniques, we can achieve very good average-case complexity. Of course
 1783 having a good worst-case complexity is important (such as the Hungarian method), but the
 1784 impact of a good average-case complexity can be significant as well. This is illustrated nicely
 1785 by the timings measured in Table [Appendix 4 Table A3](#), where our method consistently
 1786 surpasses the Hungarian method in terms of performance – especially for very large groups
 1787 of animals – despite having worse worst-case complexity. Usually, even in situations with
 1788 over 1000 individuals present, the average number of leaves visited was approximately 1.112
 1789 (see Table [Appendix 4 Table A5](#)) and each visit was a global improvement (not shown). The
 1790 number of nodes visited per frame were around 2844 to 19,804,880 in the same video, which,
 1791 given the maximal number of possible combinations N^M for M edges and N individuals
 1792 ([Thomas \(2016\)](#)), is quite moderate. Especially considering the number of calculations that
 1793 the Hungarian method has to perform in every step, which, according to its complexity, will
 1794 be in the range of $N^3 \approx 1e9$ for $N = 1024$ individuals.
- 1795 The average complexity of a solution using best-first-search BnB is given by [Weixiong](#)
 1796 ([1996](#)). It depends on the probability of encountering a "zero-cost edge" p_0 , as well as the
 1797 mean branching factor b of the tree:
- 1798 1. $\Theta(\beta^N)$ when $bp_0 < 1$, with $\beta \leq b$ and N is the depth of the tree
 1799 2. $\Theta(N^2)$ when $bp_0 = 1$

1800 3. $\Theta(N)$ when $bp_0 > 1 \Leftrightarrow b > 1/p_0$
 1801 as $N \rightarrow \infty$.
 1802 In our case the depth of the tree is exactly the number of individuals N , which we have
 1803 already substituted here. This is the number of nodes that have to be visited in the best
 1804 case. A "zero-cost edge" is an edge that does not add any cost to the current path. We
 1805 are maximizing (not minimizing) so in our case this would be "an edge with a probability
 1806 of 1". While reaching exactly 1 is improbable, it is (in our case) equivalent to "having only
 1807 one viable edge arriving at an object". p_0 depends very much on the settings, specifically
 1808 the maximum movement speed allowed, and behavior of individuals, which is why in sce-
 1809 narios with > 100 individuals the maximum speed should always be adjusted first. To put it
 1810 another way: If there are only few branching options available for the algorithm to explore
 1811 per individual, which seems to be the case even in large groups, we can assume our graph
 1812 to have a probability p_0 within $0 \ll p_0 \leq 1$. The mean branching factor b is given by the mean
 1813 number of edges arriving at an object (not an individual). Averaging at around $b \approx k+1$, with
 1814 $k \geq 1$ being the average number of assignable blobs per individual (roughly 1.005 in video 0
 1815) and 1 the null-case, we can assume bp_0 to be > 1 on average. An average complexity of
 1816 $O(N^2)$, as long as $b > 1/p_0$, is even better than the complexity of the Hungarian method
 1817 (which is also $O(N^3)$ in the average-case, **Bertsekas (1981)**), giving a possible explanation for
 1818 the good results achieved using tree-based matching in TReX on average (Table **Appendix 4**
 1819 **Table A3**).
 1820 Further optimizations could be implemented, e.g. using impact-based heuristics (as an
 1821 example of dynamic variable ordering) instead of the static and coarse maximum probabili-
 1822 ty estimate used here. Such heuristics first choose the vertex "triggering the largest search
 1823 space reduction" (**Pesant et al. (2012)**). In our case, assigning an individual first if, for exam-
 1824 ple, it has edges to many objects that each only one other individual is connected to.



Appendix 4 Figure A1. A bipartite graph (a) and its equivalent tree-representation (b). It is *bipartite* since nodes can be sorted into two disjoint and independent sets ($\{0, 1, 2\}$ and $\{3, 4\}$), where no nodes have edges to other nodes within the same set. (a) is a straight-forward way of depicting an assignment problem, with the identities on the left side and objects being assigned to the identities on the right side. Edge weights are, in TReX and this example, probabilities for a given identity to be the object in question. This graph is also an example for an unbalanced assignment problem, since there are fewer objects (orange) available than individuals (blue). The optimal solution in this case, using weight-maximization, is to assign $0 \rightarrow 3; 2 \rightarrow 4$ and leave 1 unassigned. Invalid edges have been pruned from the tree in (b), enforcing the rule that objects can only appear once in each path. The optimal assignments have been highlighted in red.



Appendix 4 Figure A2. The same set of videos as in *Table 5* pooled together, we evaluate the efficiency of our crossings solver. *Consecutive frame segments* are sequences of frames without gaps, for example due to crossings or visibility issues. We find these *consecutive frame segments* in data exported by TReX, and compare the distribution of segment-lengths to idtracker.ai's results (as a reference for an algorithm without a way to resolve crossings). In idtracker.ai's case, we segmented the non-interpolated tracks by missing frames, assuming tracks to be correct in between. The Y-axis shows the percentage of $\sum_{k \in [1, V]} \text{video_length}_k * \# \text{individuals}_k$ in V videos that one column makes up for – the overall coverage for TReX was 98%, while idtracker.ai was slightly worse with 95.17%. Overall, the data distribution suggests that, probably due to it attempting to resolve crossings, TReX seems to produce longer consecutive segments.

Appendix 4 Figure A2-source data 1. A list of all consecutive frame segments used in Appendix 4 Figure A2. In the table, they are indexed by their length, the software they were produced by, the video they originate from, as well as they bin they belong to.

Appendix 4 Figure A2-source data 2. The raw data-points as plotted in Appendix 4 Figure A2.

video characteristics			ms / frame (processing)					processing time
video	# ind.	ms / frame	5%	mean	95%	max	> real-time	% video length
0	1024	25.0	46.93	62.96	119.54	849.16	100.0%	358.12
1	512	20.0	19.09	29.26	88.57	913.52	92.11%	259.92
2	512	16.67	17.51	26.53	36.72	442.12	97.26%	235.39
3	256	20.0	8.35	11.28	13.25	402.54	1.03%	77.18
4	256	16.67	8.04	11.62	13.48	394.75	1.13%	94.77
5	128	16.67	3.54	5.14	5.97	367.92	0.41%	40.1
6	128	16.67	3.91	5.64	6.89	381.51	0.51%	44.38
7	100	31.25	2.5	3.57	5.19	316.75	0.1%	28.35
8	59	19.61	1.43	2.29	3.93	2108.77	0.19%	16.33
9	15	40.0	0.4	0.52	1.67	4688.5	0.01%	2.96
10	10	10.0	0.28	0.33	0.57	283.7	0.07%	8.08
11	10	31.25	0.21	0.25	0.65	233.7	0.01%	3.48
12	10	31.25	0.23	0.27	0.75	225.63	0.02%	2.82
13	10	31.25	0.22	0.25	0.54	237.32	0.02%	2.64
14	8	33.33	0.24	0.29	0.66	172.8	0.02%	1.8
15	8	40.0	0.22	0.26	0.88	244.88	0.01%	1.5
16	8	28.57	0.18	0.21	0.51	1667.14	0.02%	1.38
17	1	7.14	0.03	0.04	0.06	220.81	0.01%	1.56

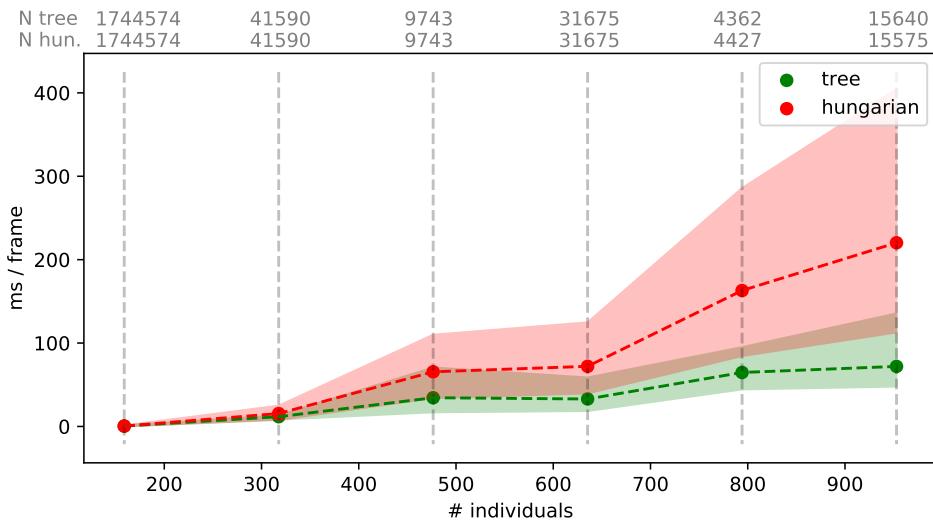
Appendix 4 Table A1. Showing quantiles for frame timings for videos of the *speed dataset* (without posture enabled). Videos **15**, **16** and **14** each contain a short sequence of taking out the fish, causing a lot of big objects and noise in the frame. This leads to relatively high spikes in these segments of the video, resulting in high peak processing timings here. Generally, processing time is influenced by a lot of factors involving not only TRex, but also the operating system as well as other programs. While we did try to control for these, there is no way to make sure. However, having sporadic spikes in the timings per frame does not significantly influence overall processing time, since it can be compensated for by later frames. We can see that videos of all quantities \leq 256 individuals can be processed faster than they could be recorded. Videos that can not be processed faster than real-time are underlaid in gray.

Appendix 4 Table A1–source data 1. Raw samples for this table and [Appendix 4 Table A5](#).

video	# ind.	length		total	excluded		wrong
7	100	1min		717	755	22	45 (6.47%)
8	59	10min		279	312	146	55 (41.35%)
9	15	1h0min		838	972	70	100 (13.02%)
13	10	10min3s		331	337	22	36 (11.65%)
12	10	10min3s		382	404	42	83 (24.41%)
11	10	10min10s		1067	1085	50	52 (7.18%)
14	8	3h15min22s		7424	7644	1428	1174 (19.58%)
15	8	1h12min		3538	3714	427	651 (20.93%)
16	8	3h18min13s		2376	3305	136	594 (26.52%)
sum				16952	16754	-2343	-2554
						2811 (19.24%)	4374 (27.38%)

Appendix 4 Table A2. A quality assessment of assignment decisions made by the general purpose tracking system without the aid of visual recognition – comparing results of two accurate tracking algorithms with the assignments made by an approximate method. Here, *decisions* are reassessments of an individual after it has been lost, or the tracker was too "unsure" about an assignment. Decisions can be either correct or wrong, which is determined by comparing to reference data generated using automatic visual recognition: Every segment of frames between decisions is associated with a corresponding "baseline-truth" identity from the reference data. If this association changes after a decision, then that decision is counted as wrong. Analysing a decision may fail if no good match can be found in the reference data (which is not interpolated). Failed decisions are ignored. Comparative values for the Hungarian algorithm (*Kuhn (1955)*) are always exactly the same as for our tree-based algorithm, and are therefore not listed separately. Left-aligned *total*, *excluded* and *wrong* counts in each column are results achieved by an accurate algorithm, numbers to their right are the corresponding results using an approximate method.

Appendix 4 Table A2-source data 1. Raw data of trial runs using the hungarian and tree-based matching algorithms, as well as baseline data from manually or automatically corrected trials used in this table is available for download from [Walter et al. \(2020\) \(in A4T2_source_data.zip\)](#).



Appendix 4 Figure A3. Mean values of processing-times and 5%/95% percentiles for video frames of all videos in the speed dataset (Table [Table 1](#)), comparing two different matching algorithms. Parameters were kept identical, except for the matching mode, and posture was turned off to eliminate its effects on performance. Our tree-based algorithm is shown in green and the Hungarian method in red. Grey numbers above the graphs show the number of samples within each bin, per method. Differences between the algorithms increase very quickly, proportional to the number of individuals. Especially the Hungarian method quickly becomes very computationally intensive, while our tree-based algorithm shows a much shallower curve. Some frames could not be solved in reasonable time by the tree-based algorithm alone, at which point it falls back to the Hungarian algorithm. Data-points belonging to these frames ($N = 79$) have been excluded from the results for both algorithms. One main advantage of the Hungarian method is that, with its bounded worst-case complexity (see Matching an object to an object in the next frame), no such combinatorical explosions can happen. However, even given this advantage the Hungarian method still leads to significantly lower processing speed overall (see also appendix Table [Appendix 4 Table A3](#)).

Appendix 4 Figure A3-source data 1. Raw data for producing this figure and [Appendix 4 Table A3](#). Each sample is represented as a row here, indexed by method (tree, approximate, hungarian), video and the bin (horizontal line in this figure).

video metrics				% real-time		
video	# ind.	fps (Hz)	size (px ²)	tree	approximate	hungarian
0	1024	40	3866 × 4048	35.49 ± 65.94	38.69 ± 65.39	12.05 ± 18.72
1	512	50	3866 × 4140	51.18 ± 180.08	75.02 ± 193.0	28.92 ± 29.12
2	512	60	3866 × 4048	59.66 ± 121.4	65.58 ± 175.51	23.18 ± 26.83
3	256	50	3866 × 4140	174.02 ± 793.12	190.62 ± 743.54	127.86 ± 9841.21
4	256	60	3866 × 4048	140.73 ± 988.15	155.9 ± 760.05	108.48 ± 2501.06
5	128	60	3866 × 4048	318.6 ± 347.8	353.58 ± 291.63	312.05 ± 337.71
6	128	60	3866 × 4048	286.13 ± 330.08	314.91 ± 303.53	232.33 ± 395.21
7	100	32	3584 × 3500	572.46 ± 98.21	611.5 ± 96.46	637.87 ± 97.03
8	59	51	2306 × 2306	744.98 ± 264.43	839.45 ± 257.56	864.01 ± 223.47
9	15	25	1880 × 1881	4626.84 ± 424.8	4585.08 ± 378.64	4508.08 ± 404.56
10	10	100	1920 × 1080	2370.35 ± 303.94	2408.27 ± 297.83	2362.42 ± 296.99
11	10	32	3712 × 3712	6489.12 ± 322.59	6571.28 ± 306.34	6472.0 ± 322.03
12	10	32	3712 × 3712	6011.59 ± 318.12	6106.12 ± 305.96	5549.25 ± 318.21
13	10	32	3712 × 3712	6717.12 ± 325.37	6980.12 ± 316.59	6726.46 ± 316.87
14	8	30	3008 × 3008	8752.2 ± 2141.03	8814.63 ± 2101.4	8630.73 ± 2177.16
15	8	25	3008 × 3008	9786.68 ± 1438.08	10118.04 ± 1380.2	9593.44 ± 1439.28
16	8	35	3008 × 3008	9861.42 ± 1424.91	10268.82 ± 1339.8	9680.68 ± 1387.14
17	1	140	1312 × 1312	15323.05 ± 637.17	15250.39 ± 639.2	15680.93 ± 640.99

Appendix 4 Table A3. Comparing computation speeds of the tree-based tracking algorithm with the widely established Hungarian algorithm [Kuhn \(1955\)](#), as well as an approximate version optimized for large quantities of individuals. Posture estimation has been disabled, focusing purely on the assignment problem in our timing measurements. The tree-based algorithm is programmed to fall back on the Hungarian method whenever the current problem "explodes" computationally – these frames were excluded. Listed are relevant video metrics on the left and mean computation speeds on the right side for three different algorithms: (1) The tree-based and (2) the approximate algorithm presented in this paper, and (3) the Hungarian algorithm. Speeds listed here are percentages of real-time (the videos' fps), demonstrating usability in closed-loop applications and overall performance. Results show that increasing the number of individuals both increases the time-cost, as well as producing much larger relative standard deviation values. (1) is almost always fast than (3), while becoming slower than (2) with increasing individual numbers. In our implementation, all algorithms produce faster than real-time speeds with 256 or fewer individuals (see also appendix Table [Appendix 4 Table A1](#)), with (1) and (2) even getting close for 512 individuals.

video metrics				minutes			
video	# ind.	length	fps (Hz)	prepare	tracking	live	win (%)
0	1024	8.33min	40	10.96 ± 0.3	41.11 ± 0.34	65.72 ± 1.35	-26.23
1	512	6.67min	50	11.09 ± 0.24	24.43 ± 0.2	33.67 ± 0.58	5.24
2	512	5.98min	60	11.72 ± 0.2	20.86 ± 0.47	31.1 ± 0.62	4.55
3	256	6.67min	50	11.09 ± 0.21	7.99 ± 0.17	12.35 ± 0.17	35.26
4	256	5.98min	60	11.76 ± 0.26	9.04 ± 0.26	15.08 ± 0.13	27.46
6	128	5.98min	60	11.77 ± 0.29	4.74 ± 0.13	12.13 ± 0.32	26.49
5	128	6.0min	60	11.74 ± 0.26	4.54 ± 0.1	12.08 ± 0.25	25.79
7	100	1.0min	32	1.92 ± 0.02	0.47 ± 0.01	2.03 ± 0.02	14.88
8	59	10.0min	51	6.11 ± 0.07	7.68 ± 0.12	9.28 ± 0.08	32.7
9	15	60.0min	25	12.59 ± 0.18	5.32 ± 0.07	13.17 ± 0.12	26.47
11	10	10.17min	32	8.58 ± 0.04	0.74 ± 0.01	8.8 ± 0.12	5.66
12	10	10.05min	32	8.68 ± 0.04	0.75 ± 0.01	8.65 ± 0.07	8.3
13	10	10.05min	32	8.67 ± 0.03	0.71 ± 0.01	8.65 ± 0.07	7.76
10	10	10.08min	100	4.17 ± 0.06	2.02 ± 0.02	4.43 ± 0.05	28.3
14	8	195.37min	30	110.51 ± 2.32	8.99 ± 0.22	109.97 ± 2.05	7.98
15	8	72.0min	25	31.84 ± 0.53	3.26 ± 0.07	32.1 ± 0.42	8.55
16	8	198.22min	35	133.45 ± 2.22	11.38 ± 0.28	133.1 ± 2.28	8.1
							mean 14.55 %

Appendix 4 Table A4. Comparing the time-cost for tracking and converting videos in two steps with doing both of those tasks at the same time. The columns *prepare* and *tracking* show timings for the tasks when executed separately, while *live* shows the time when both of them are performed at the same time using the live-tracking feature of TGrabs. The column *win* shows the time "won" by combining tracking and preprocessing as the percentage (*prepare* + *tracking* - *live*) / (*prepare* + *tracking*). The process is more complicated than simply adding up timings of the tasks. Memory and the interplay of work-loads have a huge effect here. Posture is enabled in all variants.

video characteristics		matching stats		
video	# ind.	# nodes visited (5,50,95,100%)	# leafs visited	# improvements
0	1024	[1535; 2858; 83243; 18576918]	1.113 ± 0.37	1.113
1	512	[1060; 8156; 999137; 19811558]	1.247 ± 0.61	1.247
2	512	[989; 2209; 56061; 8692547]	1.159 ± 0.47	1.159
3	256	[452; 479; 969; 205761]	1.064 ± 0.29	1.064
4	256	[475; 496; 584; 608994]	1.028 ± 0.18	1.028
5	128	[233; 245; 258; 7149]	1.012 ± 0.12	1.012
6	128	[237; 259; 510; 681702]	1.046 ± 0.25	1.046
7	100	[195; 199; 199; 13585]	1.014 ± 0.14	1.014
8	59	[117; 117; 117; 16430]	1.014 ± 0.2	1.014
9	15	[24; 29; 29; 635]	1.027 ± 0.22	1.027
10	10	[17; 19; 19; 56]	1.001 ± 0.02	1.001
11	10	[19; 19; 19; 129]	1.006 ± 0.1	1.006
12	10	[19; 19; 19; 1060]	1.023 ± 0.23	1.023
13	10	[19; 19; 19; 106]	1.001 ± 0.04	1.001
14	8	[11; 15; 15; 893]	1.003 ± 0.08	1.003
15	8	[13; 15; 15; 597]	1.024 ± 0.23	1.024
16	8	[15; 15; 15; 2151]	1.009 ± 0.17	1.009
17	1	[1; 1; 1; 1]	1.0 ± 0.02	1.0

Appendix 4 Table A5. Statistics for running the tree-based matching algorithm with the videos of the speed dataset. We achieve low leaf and node visits across the board – this is especially interesting in videos with high numbers of individuals. High values for '# nodes visited' are only impactful if they make up a large portion of the assignments. These are the result of too many choices for assignments – the weak point of the tree-based algorithm – and lead to combinatorical "explosions" (the method will take a really long time to finish). If such an event is detected, TReX automatically switches to a more computationally bounded algorithm like the Hungarian method.

1825 Appendix 5

1826 **Posture**

1827 Estimating an animals orientation and body pose in space is a diverse topic, where angle
 1828 and pose can mean many different things. We are not estimating the individual positions
 1829 of many legs and antennae in TRex, we simply want to know where the front- and the back-
 1830 end of the animal are. Ultimately, the goal here is to be able to align animals using an
 1831 arbitrary axis with their head extending in one direction and their tail roughly in the opposite
 1832 direction. In order to achieve this, we are required to follow a series of steps to acquire all
 1833 the necessary information:

- 1834 1. Locate objects in the image
- 1835 2. Detect the edge of objects
- 1836 3. Find an ordered set of points (the outline), which in sequence approximate the outer
 edge of an object in the scene. This is done for each object (as well as for holes).
- 1837 4. Calculate a center-line based on local curvature of the outline.
- 1838 5. Calculate head and tail positions.
- 1839

1840 The first point is a given at this point (see Connected components algorithm). We can
 1841 utilize the format in which connected components are computed in TRex (an ordered array
 1842 of horizontal line segments), which reduces redundancy by avoiding to look at every individ-
 1843 ual pixel. These line segments also contain information about edges since every start and
 1844 end has to be an edge-pixel, too.

1845 Even though we already have a list of edge-pixels, retrieving an *ordered* set of points is
 1846 crucial and requires much more effort. Without information about a pixels connectivity, we
 1847 can not differentiate between inner and outer shapes (holes vs. outlines) and we can not
 1848 calculate local curvature.

1849 **Connecting pixels to form an outline**

1850 We implemented an algorithm based on horizontal line segments, which only ever retains
 1851 three consecutive rows of pixels (*p* previous, *c* current and *n* next). These horizontal line
 1852 segments always stem from a "blob" (or connected component). Rows contain (i) their y-
 1853 value in pixels, (ii) x_0, x_1 values describing the first and last "on"-pixel that has been found
 1854 in it, (iii) a set of detected border pixels (identified by their x-coordinate). A row is valid,
 1855 whenever the y coordinate is not -1 – all three rows are initialized to an invalid $y = -1$. l' is
 1856 the previous row. Using *p, corn* as a function $c(x)$ returns 1 for on-pixels at that x-coordinate,
 1857 and 0 for off-pixels.

1858 For each line *l* in the sorted list of horizontal line segments, we detect border pixels:

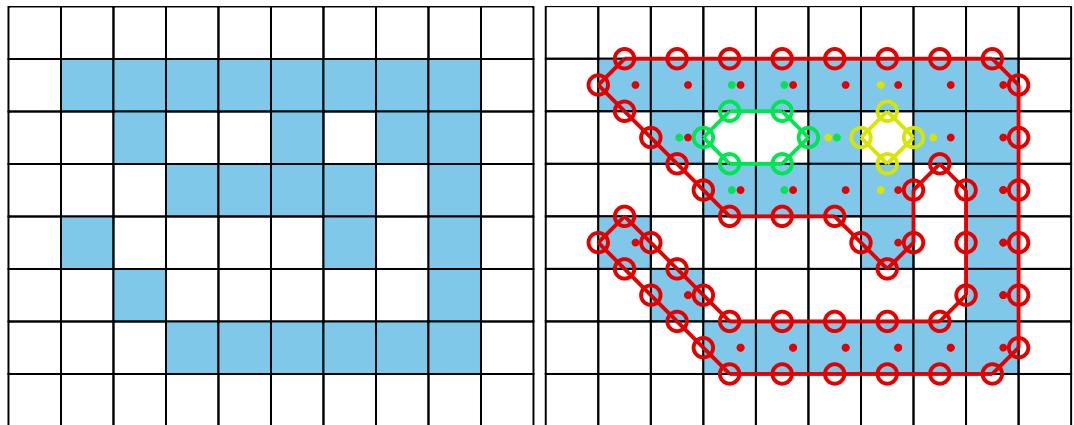
- 1859 1. subtract the blobs position (minimum of all l_{x0} and l_y separately) from *l*
- 1860 2. **if** $n_y \neq l_y$, a row has ended and a new one starts: call finalize
- 1861 **else if** $l_{x0} - l'_{x1} \geq 1 \wedge l_{x0} \geq c_{x0}$, we either skipped a few pixels in *n* or *l* starts before
 c even had valid pixels. This means that all pixels *x* between $\max\{l'_{x1} + 1; c_{x0}\} \leq x <$
 $\min\{l_{x0}; c_{x1} + 1\}$ are border pixels in *c*.
- 1862 3. **if** $l_{x1} < c_{x0}$, or *c* is invalid, then line *l* ends before the previous row (*c*) even has any
 "on"-pixels. All pixels *x* between $l_{x0} \leq x \leq l_{x1}$ are border pixels in *n*.
- 1863 **else**
- 1864 (a) $s := l_{x0}$
- 1865 (b) **if** $s < c_{x0}$, then lines are overlapping in *c* and *n* (line *l*). We can fill *n* up with border
 while $x < c_{x0}$ and $x \leq l_{x1}$. Set $s := \min\{c_{x0} - 1; l_{x1}\}$.
- 1866
- 1867

1868
 1869
 1870 **else if** $s = 0$ or $s > 0 \wedge n(s - 1) = 0$, then l starts at the image border (which is an automatic border pixel) or there is a gap before l . Set $s := s + 1$.
 1871
 1872 (c) All pixels at x -coordinates $s \leq x \leq l_{x1}$ are border in n , if they are either (i) beyond c 's bounds ($x \geq c_{x1}$), or (ii) $c(x) = 0$.
 1873
 1874 4. Set $n_{x1} := l_{x1}$.
 1875 After iterating through all lines, we need two additional calls to **finalize** to populate the lines currently in c and n through.
 1876
 1877 A graph is updated each time a row is finalized. This graph stores all border "nodes", as well as all a maximum of two edges per node (since this is the maximum number of neighbours for a line vertex). More on that below. The following procedure (**finalize**) prepares a row (c) to be integrated into the graph, using two parameters: A triplet of rows (p, c, n) and the first line l , which started the new row to be added.
 1878
 1879
 1880
 1881
 1882 1. **if** n is invalid, continue to the next operation.
 1883 **else if** $l_y > n_y + 1$, then we skipped at least one row between n and the new row – making all on-pixels in n border pixels.
 1884 **else** we have consecutive rows where $l_y = n_y + 1$. All on-pixels x in n between $n_{x0} \leq x \leq l_{x0} - 1$ are border pixels.
 1885
 1886
 1887 2. Now the current row (c) is certainly finished, as it will in the following become the previous row (p), which is read-only at that point. We can add every border-pixel of c to our graph (see below).
 1888
 1889 3. It then discards p and moves $c \rightarrow p$ and $n \rightarrow c$, as well as reading a new row to assign to n , setting $n_{x0} = l_{x0}, n_{x1} = l_{x1}, n_y = l_y$.
 1890
 1891
 1892 The graph consists of nodes (border pixels), indexed by their x and y coordinates (integers) and containing a list of all on-pixels around them (8-neighbourhood with top-left, top, left, bottom-left, etc.). This information is available when **finalize** is called, since the middle row (c) is fully defined at that point (its entire neighbourhood has been cached).
 1893
 1894
 1895
 1896 After all rows have been processed, an additional step is needed to connect all nodes and produce a connected, clockwise ordered outline. We already marked all pixels that have at least one border. We can also already mark TOP, RIGHT, BOTTOM and LEFT borders per node if no neighbouring pixel is present in that direction, since these major directions will definitely get a "line" in the end. So all we have left to do now, is check the diagonals. The points that will be returned, are located half-way along the outer edges of pixels. In the end, each pixel can potentially have four border lines (if it is a singular pixel without connections to other pixels, see yellow "hole" in **Appendix 5 Figure A1b**). The half-edge-points for each node are generated as follows:
 1897
 1898
 1899
 1900
 1901
 1902
 1903
 1904
 1905 1. A nodes list of border pixels is a sparse, ordered list of directions (top, top-right, ..., top-left). Each major direction of these (TOP, RIGHT, BOTTOM, LEFT), if present, check the face of their square to the left of them (own direction - 1, or -45°). For example, TOP would check top-left.
 1906
 1907
 1908 2. **if** the checked neighbour is on, we add an edge between our face (e.g. TOP) and its 90° rotated face (e.g. own direction + 2 = RIGHT).
 1909 **else** check the face an additional 45° to the left (e.g. LEFT).
 1910
 1911 (a) **if** it there is an on-pixel attached to this face, add an edge between the two faces (of the focal and its left pixel) in the same direction (e.g. TOP→TOP).
 1912 (b) **else** we do not seem to have a neighbour to either side, so this must be a corner pixel. Add an edge from the focal face (e.g. TOP) to the side 90° to the left of itself (e.g. LEFT).
 1913
 1914
 1915
 1916

1917 Each time an edge is added, more and more of the half-edges are becoming fully-connected
 1918 (meaning they have two of the allowed two edges). To generate the final result, all we have
 1919 to do is to start somewhere in the graph and walk strictly in clockwise direction. "Walking"
 1920 is done using a queue and edges are followed using depth-first search (see Matching an ob-
 1921 ject to an object in the next frame): Each time a node is visited, all its yet unexplored edges
 1922 are added to the front of the queue (in clockwise order). Already visited edges are marked
 1923 (or pruned) and will not be traversed again – their floating-point positions (somewhere on
 1924 an edge of its parent pixel) are added to an array.
 1925 After a path ended, meaning that no more edges can be reached from our current node,
 1926 the collected floating-point positions are pushed to another array and a different, yet unvis-
 1927 ited, starting node is sought. This way, we can accumulate all available outlines in a given
 1928 image one-by-one – including holes.
 1929 These outlines will usually be further processed using an Elliptical Fourier Transform
 1930 (or EFT, *Kuhl and Giardina (1982)*), as mentioned in the main-text. Outlines can also be
 1931 smoothed using a weighted average of the N points around a given point, or resampled to
 1932 either reduce or (virtually) increase resolution.

1933 **Finding the tail**
 1934 Given an ordered outline, curvature can be calculated locally (per index i):
 1935
 1936
 1937 $C(i) = 4 * \text{triangle_area}(p_{i-r}, p_i, p_{i+r}) / (\|p_i - p_{i-r}\| * \|p_i - p_{i+r}\| * \|p_{i-r} - p_{i+r}\|)$
 1938 where $1 \leq r \in \mathbb{N}$ is a parameter, which effectively leads to more smoothing when in-
 1939 creased. Triangle area can be calculated as follows:
 1940
 1941
 1942
 1943 $\text{triangle_area}(\mathbf{a}, \mathbf{b}, \mathbf{c}) = (\mathbf{b}_x - \mathbf{a}_x)(\mathbf{c}_y - \mathbf{a}_y) - (\mathbf{b}_y - \mathbf{a}_y)(\mathbf{c}_x - \mathbf{a}_x).$
 1944
 1945 To find the "tail", or the pointy end of the shape, we employ a method closely related to
 1946 scipys `find_peaks` function: We find local maxima using discrete curve differentiation and
 1947 then generate a hierarchy of these extrema. The only major difference to normal differen-
 1948 tiation is that we assume periodicity to achieve our results – values wrap around in both
 1949 directions, since we are dealing with an outline here. We then find the peak with the largest
 1950 integral, meaning we detect both very wide and very high peaks (just not very slim ones).
 1951 The center of this peak is the "tail".
 1952 To find the head as well, we now have to search for the peak that has the largest (index-
 1953) distance to the tail-peak. This is a periodic distance, too, meaning that N is one of the
 1954 closest neighbours of 0.
 1955 The entire outline array is then rotated, so that the head is always the first point in it.
 1956 Both indexes are saved.

1957 **Calculating the center-line**
 1958 A center-line, for a given outline, can be calculated by starting out at the head and walking
 1959 in both directions from there – always trying to find a pair of points with minimal distance
 1960 to each other on both sides. Two indices are used: l, r for left and right. We also allow
 1961 some "wiggle-room" for the algorithm to find the best-matching points on each side. This
 1962 is limited by a maximum offset of ω points which is set to $0.025 * N$ by default, where N is
 1963 the number of points in the outline. $\mathbf{f}(i)$ gives the point on in outline at position i .
 1964 Starting from $l := -1, r := 1$ we continue while $r < l + N$:
 1965 1. Find $m := \arg\min_i \{\|\mathbf{f}(r+i) - \mathbf{f}(l)\| ; \forall i \leq \omega \wedge r+i < N\}$. If no valid m can be found, abort.
 1966 Otherwise set $r := m$.



Appendix 5 Figure A1. The original image is displayed on the left. Each square represents one pixel. The processed image on the right is overlaid with lines of different colors, each representing one connected component detected by our outline estimation algorithm. Dots in the centers of pixels are per-pixel-identities returned by OpenCVs `findContours` function (for reference) coded in the same colors as ours. Contours calculated by OpenCVs algorithm can not be used to estimate the one-pixel-wide "tail" of the 9-like shape seen here, since it becomes a 1D line without sub-pixel accuracy. Our algorithm also detects diagonal lines of pixels, which would otherwise be an aliased line when scaled up.

- ```

1967 2. Find $k := \operatorname{argmin}_i \{ \|\mathbf{f}(l - i + N) - \mathbf{f}(r)\| ; \forall i \leq \omega \wedge l - i \leq -N \}$. If no valid k can be found,
1968 abort. Otherwise set $l := k$.
1969 3. Our segment now consists of points $\mathbf{f}(m)$ and $\mathbf{f}(k)$, with a center vector of $(\mathbf{f}(k) - \mathbf{f}(m)) *$
1970 $0.5 + \mathbf{f}(m)$. Push it to the center-line array. We can also calculate the width of the body
1971 at that point using $\|\mathbf{f}(k) - \mathbf{f}(m)\|$.
1972 4. Set $l := l - 1$.
1973 5. Set $r := r + 1$.

```

1974 Head and tail positions can be switched now, e.g. for animals where the wider part is the  
 1975 head. We may also want to start at the slimmest peak first, which ever that is, since there  
 1976 we have not as much space for floating-point errors regarding where *exactly* the peak was.  
 1977 These options depend on the specific settings used in each video.

1978 The angle of the center-line is calculated using `atan2` for a vector between the first point  
 1979 and one point at an offset from it. The specific offset is determined by a `midline stiffness`  
 1980 parameter, which offers some additional stability – despite e.g. potentially noisy peak de-  
 1981 tection.

## 1982 Appendix 6

1983

**Visual field estimation**

1984

Visual fields are calculated by casting rays and intersecting them with other individuals and the focal individual (for self-occlusion). An example of this can be seen in **Figure 7**. The following procedure requires posture for all individuals in a frame. In case an individual does not have a valid posture in the given frame, its most recent posture and position are used as an approximation. The field is internally represented as a discretized vector of multi-dimensional pixel values. Depending on the resolution parameter ( $F_{\text{res}}$ ), which sets the number of pixels, each index in the array represents step-sizes of  $(F_{\text{max}} - F_{\text{min}})/F_{\text{res}}$  radians. The  $F$  values are constants setting the minimum and maximum field of view ( $-130^\circ$  to  $130^\circ$  by default, which gives a range of  $260^\circ$ ). Each pixel consists of multiple data-streams: The distance to the other individual, the identity of the other individual and the body-part that the ray intersected with.

1985

Eyes are simulated to be located on the outline of the focal individual, near the head. The distance to the head can be set by the user as a percentage of midline-length. To find the exact eye position, the program calculates intersections between vectors going left/right from that midline point, perpendicular to the midline, and the individual's outline. In order to be able to simulate different types of binocular and monocular sight, a parameter for eye separation  $E_{\text{sep}}$  (radians) controls the offset from the head angle  $H_a$  per eye. Left and right eye are looking in directions  $H_a - E_{\text{sep}}$  and  $H_a + E_{\text{sep}}$ , respectively.

1986

We iterate through all available postures in a given frame and use a procedure which is very similar to depth-maps (**Williams (1978)**) in e.g. OpenGL. In the case of 2D visual fields, this depth-map is 1D. Each pixel holds a floating-point value (initialized to  $\infty$ ) which is continuously compared to new samples for the same position – if the new sample is closer to the "camera" than the reference value, the reference value is replaced. This way, after all samples have been evaluated, we generate a map of the objects closest to the "camera" (in this case the eye of the focal individual). For that to work we also have to keep the identity in each of these discrete slots maintained. So each time a depth value is replaced, the same goes for all the other data-streams (such as identity and head-position). When an existing value is replaced, values in deeper layers of occlusion are pushed downwards alongside the old value for the first layer.

1987

Position of the intersecting object's top-left corner is located at  $\hat{P}$ . Let  $E_e$  be the position of each eye, relative to  $\hat{P}$ . For each point  $P_j$  (coordinates relative to  $\hat{P}$ ) of the outline, check the distance between  $E_e$  and the outline segments  $(P_j - P_{j-1})$ . For each eye  $E_e$ :

1988

1. Project angles ranging from  $[\text{atan}2(P_{j-1} + E_e), \text{atan}2(P_j + E_e)]$ , where  $\alpha_e$  is the eye orientation, using:

1989

$$\Gamma_e(\beta) = \text{angle\_normalize}(\beta - \alpha_e - F_{\text{min}}) / (F_{\text{max}} - F_{\text{min}}) * F_{\text{res}}$$

1990

$\text{angle\_normalize}(\beta)$  normalizes beta to be between  $[-\pi, \pi]$ .

1991

2. **if** either  $\max(R)$  or  $\min(R)$  is inside the visual field ( $0 \leq \Gamma_e(\beta) \leq 1$ ):

1992

(a) We call the first angle satisfying the condition  $\beta$ .

1993

(b) Then the search range becomes  $R := [\lfloor \max\{\beta - 0.5; 0\} \rfloor, \lceil \beta + 0.5 \rceil]$ , where the elements in  $R$  are integers.

1994

(c) Let  $\delta_{j,e} = \|P_{j-1} - E_e\|$ , the distance between outline point at  $j - 1$  and the eye (interpolation could be done here).

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(d) Let index  $k \in \mathbb{N}, k \in R$  be our index into the first layer of the depth-map  $\text{depth}_0$ :

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(e) **if**  $\text{depth}_0(k) > \delta_{j,e}$ : Calculate all properties  $D_0(k) := \{\text{head\_distance}, \dots \in \text{data\_streams}\}^T$ ,  
and push values at  $k$  in layer 0 to layer 1.

(f) **otherwise**, if  $\text{depth}_1(k) > \delta_{j,e}$ , calculate properties for layer 1 instead and move  
data from layer 1 further down, etc.

**2033** The data-streams are calculated individually with the following equations:

- **Distance:** Given already in  $\text{depth}_i(k)$ . In practice, values are cut off at the maximum distance (size of the video squared) and normalized to  $[0, 255]$ .
  - **Identity:** Is assigned alongside  $\text{depth}_i(k)$  for each element that successfully replacing another in the map.
  - **Body-part:** Let  $T_i$  = tail index,  $L_{l/r}$  = number of points in left/right side of the outline (given by tail- and head-indexes):
    1. **if**  $i > T_i$ :  $\text{head\_distance} = 1 - |i - T_i|/L_l$
    2. **else**:  $\text{head\_distance} = 1 - |i - T_i|/L_r$

2042 **Appendix 7**

2043 **The PV file format**

2044 Since we are using a custom file format to save videos recorded using `TGrabs` (MP4 video can  
 2045 be saved alongside PV for a limited time or frame-rate), the following is a short overview  
 2046 of PV6 contents and structure. This description is purely technical and concise. It is mainly  
 2047 intended for users who wish to implement a loader for the file format (e.g. in Python) or are  
 2048 curious.

2049 **Structure**

2050 Generally, the file is built as a header (containing meta information on the video) followed  
 2051 by a long data section and an index table plus a settings string at the end. The header at  
 2052 the start of the file can be read as follows:

- 2053 1. version (string): "PV6"
- 2054 2. channels (uint8): Hard-coded to 1
- 2055 3. width & height (uint16): Video size
- 2056 4. crop offsets (4x uint16): Offsets from original image
- 2057 5. size of HorizontalLine struct (uchar)
- 2058 6. # frames (uint32)
- 2059 7. index offset (uint64): Byte offset pointing to the index table for
- 2060 8. timestamp (uint64): time since 1970 in microseconds of recording (or conversion time  
     if unavailable)
- 2061 9. empty string
- 2062 10. background image (byte\*): An array of uint8 values of size width \* height \* channels.
- 2063 11. mask image size (uint64): 0 if no mask image was used, otherwise size in bytes fol-  
     lowed by a byte\* array of that size

2066 Followed by the data section, where information is saved per frame. This information  
 2067 can either be in a zip-compressed format, or raw (determined by size), see below:

- 2068 1. compression flag (uint8): 1 if compression was used, 0 otherwise
- 2069 2. if compressed:
  - 2070 (a) original size (uint32)
  - 2071 (b) compressed size (uint32)
  - 2072 (c) lzo1x compressed data (byte\*) in the format of the uncompressed variant (below)
- 2073 3. if uncompressed:
  - 2074 (a) timestamp since start time in header (uint32)
  - 2075 (b) number of images in frame (uint16)
  - 2076 (c) for each image in frame:
    - 2077 i. number of HorizontalLines (uint16)
    - 2078 ii. data of HorizontalLine (byte\*)
    - 2079 iii. pixel data for each pixel in the previous array (byte\*)

2080 Files are concluded by the index table, which gives a byte offset for each video frame  
 2081 in the file, and a settings string. This index is used for quick frame skipping in `TRex` as well  
 2082 as random access. It consists of exactly one uint64 index per video frame (as determined  
 2083 by the number of video frames read earlier). After that map ends, a string follows, which  
 2084 contains a JSON style string of all metadata associated by the user (or program) with the  
 2085 video (such as species or size of the tank).

## 2086 Appendix 8

2087 **Automatic visual identification**2088 **Network layout and training procedure**

2089 Network layout is sketched in *Figure 1c*. Using version 2.2.4 of Keras<sup>g</sup>, weights of densely  
 2090 connected layers as well as convolutional layers are initialized using Xavier-initialization (*Glorot*  
 2091 and *Bengio (2010)*). Biases are used and initialized to 0. The default image size in TRex is  
 2092 80×80, but can be changed to any size in order to retain more detail or improve computation  
 2093 speed.

2094 During training, we use the Adam optimizer (*Kingma and Ba (2015)*) to traverse the loss  
 2095 landscape, which is generated by categorical focal loss. *Categorical* focal loss is an adapta-  
 2096 tion of the original *binary* focal loss (*Lin et al. (2020)*) for multiple classes:

$$2099 \text{cFL}(j) = \sum_{c=1}^N -\alpha (1 - \mathbf{P}_{jc})^\gamma \mathbf{V}_{jc} \log (\mathbf{P}_{jc}),$$

2101 where  $\mathbf{P}_{jc}$  is the prediction vector component returned by the network for class  $c$  in  
 2102 image  $j$ .  $\mathbf{V}$  is a set of validation images, which remains the same throughout the training  
 2103 process. It comprises 25% of the images available per individual. Images are marked *globally*  
 2104 when becoming part of the validation dataset and are not used for training in the current  
 2105 or any of the following steps.

2106 After each epoch, predictions are generated by performing a forward-pass through the  
 2107 network layers. Returned are the softmax-activations  $\mathbf{P}_{jc}$  of the last layer for each image  $j$   
 2108 in the validation dataset. Simply calculating the mean of

$$2110 \bar{A} = \frac{1}{M} \sum_{j \in [0, M]} \begin{cases} 1 & \text{if } \mathbf{P}_j = \mathbf{V}_j, \\ 0 & \text{otherwise} \end{cases},$$

2113 gives the mean accuracy of the network.  $M$  is the number of images in the validation  
 2114 dataset, where  $\mathbf{V}_j$  are the expected probability vectors per image  $j$ . However, much more  
 2115 informative is the per-class (per-identity) accuracy of the network among the set of images  
 2116  $i$  belonging to class  $c$ , which is

$$2119 I_c = \{j; \text{where } \mathbf{V}_{jc} = 1, j \in [0, M]\},$$

2121 given that all vectors in  $\mathcal{V}$  are one-hot vectors – meaning the vector has length  $N$  with  
 2122  $\mathbf{V}_{j\phi} = 0 \forall \phi \neq c$  and  $\mathbf{V}_{jc} = 1$ .

$$2124 A_c = \frac{1}{|I_c|} \sum_{j \in I_c} \begin{cases} 1 & \text{if } \mathbf{P}_j = \mathbf{V}_j \\ 0 & \text{otherwise} \end{cases}$$

2127 Another constant, across training units – not just across epochs, is the set of images used  
 2128 to calculate mean uniqueness  $\bar{U}$  (see Box 1, as well as Guiding the Training Process). Values  
 2129 generated in each epoch  $t$  of every training unit are kept in memory and used to calculate  
 2130 their derivative  $\bar{U}'(t)$ .

2131 **Stopping-criteria**

2132 A training unit can be interrupted if one of the following conditions becomes true:

- 2133  
2135  
2134  
2136
1. Training commenced for at least  $t = 5$  epochs, but uniqueness value  $\bar{U}$  was never above

$$\bar{U}_{\text{best}}^2 > \bar{U}(t) \forall t$$

2139 where  $\bar{U}_{\text{best}}$  is the best mean uniqueness currently achieved by any training unit (initialized with zero). This prevents to train on faulty segments after a first successful epoch.

- 2140  
2141  
2142
2. The worst accuracy value per class has been "good enough" in the last three epochs:

2143  
2144  
2145  
2146

$$\min_{c \in [0, N]} \{A_c\} \geq 0.97$$

- 2147  
2148  
2149
3. The global uniqueness value has been plateauing for more than 10 epochs.

$$\sum_{k \in [t-10, t]} \bar{U}'(k) \leq 0.01$$

- 2150  
2152  
2151  
2153
4. Overfitting: Change in loss is very low on average after more than 5 epochs. Mean loss is calculated as follows:

2154  
2155  
2158

$$\text{cFL}_\mu(t) = \frac{1}{5} \sum_{k \in [t-6, t-1]} \text{cFL}(k)$$

2159 Now if the difference between the current loss and the previous loss is below a threshold:

2161

2162  
2163  
2164

$$\lambda(t) = \lfloor \ln(\text{cFL}(t)) \rfloor - 1$$

$$\frac{1}{5} \sum_{k \in [t-5, t]} \max \left\{ \epsilon; |\text{cFL}(k) - \text{cFL}_\mu(k)| \right\} < 0.05 * 10^{\lambda(t)}$$

- 2165  
2166  
2167  
2168
5. Maximum number of epochs has been reached. User-defined option limiting the amount of time that training can take per unit. By default this limit is set to 150 epochs.
  6. Loss is zero. No further improvements are possible within the current training unit, so we terminate and continue with the next.

2169  
2170  
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2174

A high per-class accuracy over multiple consecutive epochs is usually an indication that everything that can be learned from the given data has already been learned. No further improvements should be expected from this point, unless the training data is extended by adding samples from a different part of the video. The same applies to scenarios with consistently zero or very low change in loss. Even if improvements are still possible, they are more likely to happen during the final (overfitting) step where all of the data is combined.

<sup>a</sup>See [keras.io](#) documentation for default arguments

## 2175 Appendix 9

2176 **Data used in this paper and reproducibility**

2177 All of the data, as well as the figures and tables showing the data, have been generated  
 2178 automatically. We provide the scripts that have been used, as well as the videos if requested.  
 2179 "Data" refers to converted video-files, as well as log- and NPZ-files. Analysis has been done  
 2180 in Python notebooks, using mostly matplotlib and pandas, as well as numpy to load the data.  
 2181 Since TRex and TGrabs, as well as idtracker.ai have been run on a Linux system, we were  
 2182 able to run everything from two separate bash files:

- 2183     1. run.bash  
 2184     2. run\_idtracker.bash

2185 Where (1) encompasses all trials run using TRex and TGrabs, both for the speed- and  
 2186 recognition-datasets. (2) runs idtracker.ai in its own dedicated Python environment, using  
 2187 only the recognition-dataset. The parameters we picked for idtracker.ai vary between  
 2188 videos and are hand-crafted, saved in individual .json files (see Table *Appendix 9 Table A1*  
 2189 for a list of settings used). We ran multiple trials for each combination of tools and data  
 2190 with  $N = 5$  where necessary:

- 2191     • 3x TGrabs [speed-dataset]
- 2192     • 5x TRex + recognition [recognition-dataset]
- 2193     • 3x idtracker.ai [recognition-dataset]
- 2194     • TRex without recognition enabled [speed-dataset]:
  - 2195         – 3x for testing the tree-based, approximate and Hungarian methods (Tracking),  
 2196         without posture enabled – testing raw speeds (see Table *Appendix 4 Table A3*)
  - 2197         – 3x testing accuracy of basic tracking (see Table *Appendix 4 Table A2*), with posture  
 2198         enabled

2199 A Python script used for *Figure 5*, which is run only once. It generates a series of results  
 2200 for the same video (video 7 with 100 individuals) with different sample-sizes. It uses a single  
 2201 set of training samples and then – after equalizing the numbers of images per individual –  
 2202 generates multiple virtual subsets with fewer images. They span 15 different sample-sizes  
 2203 per individual, saving a history of accuracies for each run. We repeated the same procedure  
 2204 with for the different normalization methods (no normalization, moments and posture),  
 2205 each repeated five times.

2206 As described in the main text, we recorded memory usage with an external tool (syrupy)  
 2207 and used it to measure both software solutions. This tool saves a log-file for each run, which  
 2208 is appropriately renamed and stored alongside the other files of that trial.

2209 All runs of TRex are preceded by running a series of TGrabs commands first, in order  
 2210 to convert the videos in the datasets. We chose to keep these trials separately and load  
 2211 whenever possible, to avoid data-duplication. Since subsequent results of TGrabs are always  
 2212 identical (with the exception of timings), we only keep one version of the PV files (The PV  
 2213 file format) as well as only one version of the results files generated using live-tracking.  
 2214 However, multiple runs of TGrabs were recorded in the form of log-files to get a measure of  
 2215 variance between runs in terms of speed and memory.

2216 **Human validation**

To ensure that results from the automatic evaluation (in Visual Identification: Accuracy) are plausible, we manually reviewed part of the data. Specifically, the table in *Table 3* shows

| video | length (# frames) | nblobs | area        | max. intensity | roi |
|-------|-------------------|--------|-------------|----------------|-----|
| 7     | 1921              | 100    | [165, 1500] | 170            | Yes |
| 8     | 30626             | 59     | [100, 2500] | 160            | Yes |
| 11    | 19539             | 10     | [200, 1500] | 10             | Yes |
| 13    | 19317             | 10     | [200, 1500] | 10             | Yes |
| 12    | 19309             | 10     | [200, 1500] | 10             | Yes |
| 9     | 90001             | 8      | [190, 4000] | 147            | Yes |
| 16    | 416259            | 8      | [200, 2500] | 50             | No  |
| 14    | 351677            | 8      | [200, 2500] | 50             | No  |
| 15    | 108000            | 8      | [250, 2500] | 10             | No  |

**Appendix 9 Table A1.** Settings used for `idtracker.ai` trials, as saved inside the `.json` files used for tracking. The minimum intensity was always set to 0 and background subtraction was always enabled. An ROI is an area of interest in the form of an array of 2D vectors, typically a convex polygon containing the area of the tank (e.g. for fish or locusts). Since this format is quite lengthy, we only indicate here whether we limited the area of interest or not.

2217  
 2218  
 2219 an overview of the individual events reviewed and percentages of wrongly assigned frames.  
 2220 Due to the length of videos and the numbers of individuals inside the videos we did not re-  
 2221 view all videos in their entirety, as shown in the table. Using the reviewing tools integrated  
 2222 in TRex, we focused on crossings that were automatically detected. These tools allow the  
 2223 user to jump directly to points in the video that it deems problematic. Detecting problematic  
 2224 situations is equivalent to detecting the end of individual segments (see Automatic Visual  
 2225 Identification Based on Machine Learning). While iterating through these situations, we  
 2226 corrected individuals that have been assigned to the wrong object, generating a clean and  
 2227 corrected baseline dataset. We assumed that an assignment is correct, as long as the indi-  
 2228 vidual is at least part of the object that the identity has been assigned to. Misassignments  
 2229 were typically fixed after a few frames. Identities always returned to the correct individuals  
 2230 afterward (thus not causing a chain of follow-up errors).

2231 **Comparison between trajectories from different softwares, or multiple runs**  
 2232 **of the same software**

2233 In our tests, the same individuals may have been given different IDs (or "names") by each  
 2234 software (and in each run of each software for the same video), so, as a first step in every  
 2235 test where this was relevant, we had to determine the optimal pairing between identities of  
 2236 two datasets we wished to compare. This was done using a square distance matrix contain-  
 2237 ing overall euclidean distances between identities is calculated by summing their per-frame  
 2238 distances. Optimally this number would be zero for one and greater than zero for every  
 2239 other pairing, but temporary tracking mistakes and differences in the calculation of cen-  
 2240 troids may introduce noise. Thus, we solved the matching problem (see Matching an object  
 2241 to an object in the next frame) for identities between each two datasets and paired individ-  
 2242 uals with the smallest accumulative distance between them. This was done for all results  
 2243 presented, where a direct comparison between two datasets was required.

## 2244 Appendix 10

### 2245 Matching probabilities

2246 One of the most important steps, when matching objects in one frame with objects in the  
 2247 next frame, is to calculate a numerical landscape that can then be traversed by a maximiza-  
 2248 tion algorithm to find the optimal combination. This landscape, which can be expressed  
 2249 as an  $m \times n$  matrix  $\mathbf{P}(t)$ , contains the probability values between [0, 1] for each assignment  
 2250 between individuals  $i$  and objects  $B_j$ .

2251 Below are definitions used in the following text:

- 2252 •  $T_\Delta$  is the typical time between frames (s), which depends on the video
- 2253 •  $\tau_i < t$  is most recent frame assigned to individual  $i$  previous to the current frame  $t$
- 2254 •  $P_{\min}$  is the minimally allowed probability for the matching algorithm, underneath which  
   the probabilities are assumed to be zero (and respective combination of object and  
   individual is ignored). This value is set to 0.1 by default.
- 2255 •  $F(t \in \mathbb{R}) \rightarrow \mathbb{N}$  is the frame number associated with the time  $t$  (s)
- 2256 •  $\mathcal{T}(f \in \mathbb{N}) \rightarrow \mathbb{R}$  is the time in seconds of frame  $f$ , with  $F(\mathcal{T}(f)) = f$
- 2257 •  $\mathbf{x}$  indicates that  $x$  is a vector
- 2258 •  $\mathbf{U}(\mathbf{x}) = \mathbf{x} / \|\mathbf{x}\|$

2261 Some values necessary for the following calculations are independent of the objects in  
 2262 the current frame and merely depend on data from previous frames. They can be re-used  
 2263 per frame and individual in the spirit of dynamic programming, reducing computational  
 2264 complexity in later steps:

$$2268 \quad \mathbf{v}_i(t) = \mathbf{p}'_i(t) = \frac{\delta}{\delta t} \mathbf{p}_i(t)$$

$$2269 \quad \hat{\mathbf{v}}_i(t) = \mathbf{v}_i(t) * \begin{cases} 1 & \text{if } \|\mathbf{v}_i(t)\| \leq D_{\max} \\ D_{\max} / \|\mathbf{v}_i(t)\| & \text{otherwise} \end{cases}$$

$$2273 \quad \mathbf{a}_i(t) = \frac{\delta}{\delta t} \hat{\mathbf{v}}_i(t)$$

2275 Velocity  $\mathbf{v}_i(t)$  and acceleration  $\mathbf{a}_i(t)$  are simply the first and second derivatives of the indi-  
 2276 viduals position at time  $t$ .  $\hat{\mathbf{v}}_i(t)$  is almost the same as the raw velocity, but its length is limited  
 2277 to the maximally allowed travel distance per second ( $D_{\max}$ , parameter `track_max_speed`).

2278 These are then further processed, combining and smoothing across values of multiple  
 2279 previous frames (the last 5 valid ones). Here,  $\bar{f}(x)$  indicates that the resulting value uses  
 2280 data from multiple frames.

$$2283 \quad \bar{s}_i(t) = \underset{k \in [F(\tau)-5, F(t)]}{\text{median}} \|\hat{\mathbf{v}}_i(\mathcal{T}(k))\|$$

2285 is the speed at which the individual has travelled at recently. The mean direction of  
 2286 movement is expressed as

$$2289 \quad \bar{\mathbf{d}}_i(t) = \frac{1}{F(t) - F(\tau) + 5} \sum_{k \in [F(\tau)-5, F(t)]} \hat{\mathbf{v}}_i(\mathcal{T}(k))$$

2291 with the corresponding direction of acceleration

$$2294 \quad \bar{\mathbf{a}}_i(t) = \mathbf{U} \left( \frac{1}{F(t) - F(\tau) + 5} \sum_{k \in [F(\tau)-5, F(t)]} \mathbf{a}_i(\mathcal{T}(k)) \right).$$

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2301  
2302  
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The predicted position for individual  $i$  at time  $t$  is calculated as follows:

$$\dot{\mathbf{p}}_i(t) = s_i(t) \sum_{k \in [F(\tau_i), F(t)-1]} w(k) (\bar{\mathbf{d}}_i(t) + \mathcal{T}'(k) * \bar{\mathbf{a}}_i(t)),$$

with weights for each considered time-step of

$$w(f) = \frac{1 + \lambda^4}{1 + \lambda^4 \max \{1, f - F(\tau_i) + 1\}},$$

where  $\lambda \in [0, 1]$  is a decay rate (parameter `track_speed_decay`) at which the impact of previous positions on the predicted position decreases with distance in time. With its value approaching 1, the resulting curve becomes steeper - giving less weight previous positions the farther away they are from the focal frame.

In order to locate an individual  $i$  in the current frame  $F(t)$ , a probability is calculated for each object  $B_j$  found in the current frame resulting in the matrix:

$$\mathbf{P}(t) = \begin{bmatrix} P_0(t | B_0) & \dots & P_n(t | B_0) \\ \vdots & \ddots & \vdots \\ P_0(t | B_m) & \dots & P_n(t | B_m) \end{bmatrix}. \quad (3)$$

Probabilities  $P_i(t | B_j)$  for all potential connections between blobs  $B_j$  and identities  $i$  at time  $t$  are calculated by first predicting the expected position  $\dot{\mathbf{p}}_i(t)$  for each individual in the current frame  $F(t)$ . This allows the program to focus on a small region of where the individual is expected to be located, instead of having to search the whole arena each time.

Based on the individual's recent speed  $\bar{s}_i(t)$ , direction  $\bar{\mathbf{d}}_i(t)$ , acceleration  $\bar{\mathbf{a}}_i(t)$  and angular momentum  $\bar{\alpha}'_i(t)$ , the individual's projected position  $\dot{\mathbf{p}}_i(t)$  is usually not far away from its last seen location for small time-steps. Only when  $\Delta t$  increases, if the individual has been lost for more than one frame or frame-rates are low, does it really play a role.

The actual probability values in  $\mathbf{P}(t)$  are then calculated by combining three metrics - each describing different aspects of potential concatenation of object  $b$  at time  $t$  to the already existing track for individual  $i$ :

The time metric  $T_i(t)$ , which does not depend on the blob the individual is trying to be matched to. It merely reflects the recency of the individuals last occurrence in a way that recently seen individual will always be preferred over individuals that have been lost for longer.

$$F_{\min} = \min \left\{ \frac{1}{T_\Delta}, 5 \right\}$$

$$R_i(t) = \left\| \left\{ \mathcal{T}(k) \mid F(t) - T_\Delta^{-1} \leq k \leq t \wedge \mathcal{T}(k) - \mathcal{T}(k-1) \leq T_{\max} \right\} \right\|$$

$$T_i(t) = \left( 1 - \min \left\{ 1, \frac{\max \{0, \tau_i - t - T_\Delta\}}{T_{\max}} \right\} \right) * \begin{cases} \min \left\{ 1, \frac{R_i(\tau_i)-1}{F_{\min}} + P_{\min} \right\} & F(\tau_i) \geq F(t_0) + F_{\min} \\ 1 & \text{otherwise} \end{cases} \quad (4)$$

$S_i(t | B_j)$  is the speed that it would take to travel from the individuals position to the blobs position in the given time (which might be longer than one frame), inverted and normalized to a value between 0 and 1.

$$S_i(t | B_j) = \left( 1 + \frac{\left\| (\mathbf{p}_{B_j}(t) - \dot{\mathbf{p}}_i(t)) / (\tau_i - t) \right\|^2}{D_{\max}} \right)^{-2} \quad (5)$$

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And the angular difference metric  $A_i(t, \tau_i | B_j)$ , describing how close in angle the resulting vector of connecting blob and individual to a track would be to the previous direction vector:

$$\mathbf{a} = \dot{\mathbf{p}}_i(t) - \mathbf{p}_i(\tau_i)$$

$$\mathbf{b} = \mathbf{p}_{B_j}(t) - \mathbf{p}_i(\tau_i)$$

$$A_i(t, \tau_i | B_j) = \begin{cases} 1 - \frac{1}{\pi} |\text{atan2}\{\|\mathbf{a} \times \mathbf{b}\|, \mathbf{a} \cdot \mathbf{b}\}| & \text{if } \|\mathbf{a}\| > 1 \wedge \|\mathbf{b}\| > 1 \\ 1 & \text{otherwise} \end{cases} \quad (6)$$

The conditional ensures that the individual travelled a long enough distance, as the atan2 function used to determine angular difference here lacks numerical precision for very small magnitudes. This is, however, an unproblematic case in this situation as the positions are in pixel-coordinates and anything below a movement of one pixel is likely to be due to noise anyway.

Combining (4), (5) and (6) into a weighted probability product yields:

$$P_i(t, \tau_i | B_j) = S_i(t | B_j) * (1 - \omega_1 (1 + A_i(t, \tau_i | B_j))) * (1 - \omega_2 (1 + T_i(t, \tau_i))) \quad (7)$$

Results from equation (7) can now easily be used in a matching algorithm, in order to determine the best combination of objects and individuals as in Matching an object to an object in the next frame.  $\omega_1$  is usually set to 0.1,  $\omega_2$  is set to 0.25 by default.

## 2371 Appendix 11

2372           **Algorithm for splitting touching individuals**

2373       **Data:** image of a blob,  $N_e$  number of expected blobs

2374       **Result:**  $N \geq N_e$  smaller image-segments, or *error*

2375       threshold =  $T_c$ ;

2376       **while** threshold < 255 **do**

2377            blobs = apply\_threshold(image, threshold);

2378            **if** ||blobs|| = 0 **then**

2379              | **break**;

2380            **end**

2381            **if** ||blobs||  $\geq N_e$  **then**

2382              | sort blobs by size in decreasing fashion;

2383              | loop through all blobs  $i$  up to  $i \leq N_e$  and detect whether the size-ratio

2384              | between them is roughly even. until then, we keep iterating.;

2385              **if** min{ratio <sub>$i$</sub> ,  $\forall i \in [0, N_e]$ } < 0.3 **then**

2386                | threshold = threshold + 1;

2387                | **continue**;

2388              **else**

2389                | **return** blobs;

2390              **end**

2391              **else**

2392                | threshold = threshold + 1;

2393              **end**

2394            **end**

2395            **return** fail;

2396       **Algorithm 2:** The algorithm used whenever two individuals touch, which is detected by a history-based method. This history-based method also provides  $N_e$ , the number of expected objects within the current (big) object.  $T_e$  is the starting threshold constant parameter, as set by the user.

## 2397 Appendix 12

2398  
2399 **Posture and Visual Identification of Highly-Deformable Bodies**

2400 To evaluate further whether TRex's posture and visual identification algorithms are broadly  
 2401 applicable, such as to mammals (e.g. rodents) – which have highly-deformable bodies and  
 2402 thus increased variance per individual, we conducted additional analyses on videos of groups  
 2403 of four freely behaving mice (four C57BL/6 mice provided by D. Mink and M. Groettrup, and  
 2404 four "black mice" from *Romero-Ferrero et al. (2019)* provided to us by G.G. de Polavieja, and  
 2405 now linked under [idtrackerai.readthedocs.io](https://idtrackerai.readthedocs.io)).

2406 Both videos, listed in *Appendix 12 Table A1* and previewed in *Appendix 12 Figure A1*,  
 2407 were analyzed using the same scripts used to generate *Table 3*, although each video has  
 2408 only been automatically tracked once (since accuracy of tracking is very high, as detailed be-  
 2409 low). We manually generated verified trajectories for both videos in full, following the same  
 2410 procedure described in *Human validation*, and compared them to the automatically gener-  
 2411 ated trajectories. As can be seen in *Appendix 12 Table A1*, TRex provides highly accurate  
 2412 results for both videos ( $\geq 99.6\%$ ).

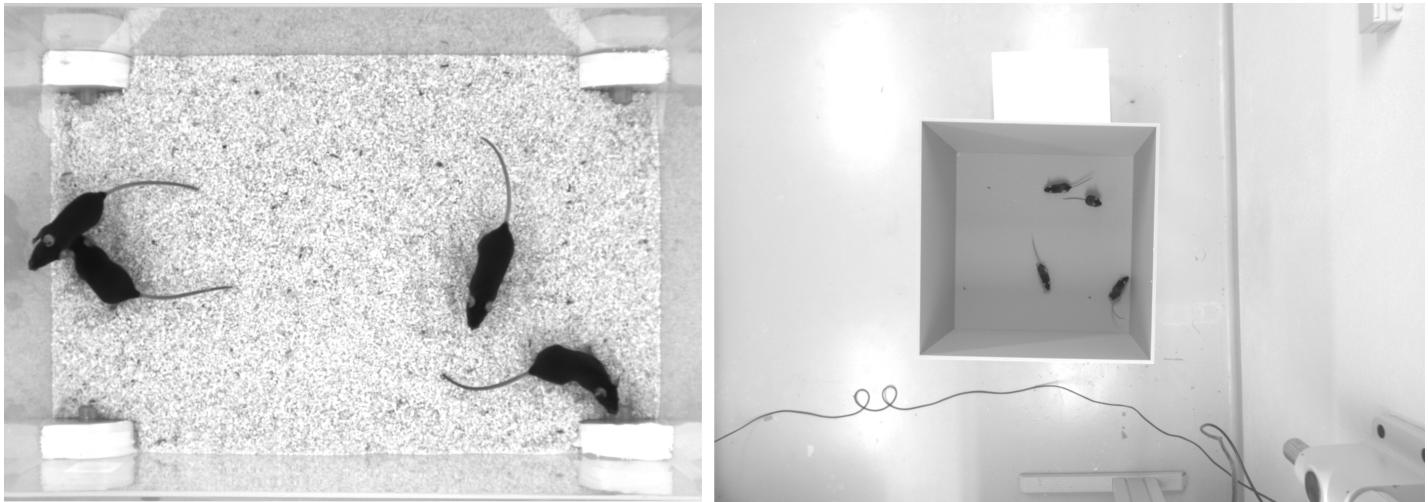
2413 Tracking, in theory and in practice as per our results here, is not generally impacted by  
 2414 the shape of individuals. However, individuals of some species tend to stay close/on top of  
 2415 con-specifics, which may render them impossible to track during periods where traditional  
 2416 image processing methods are unable to separate them. This explains the  $\sim 6\%$  interpolated  
 2417 frames in V1 (see *Appendix 12 Table A1*), and also gives a reason why there is similarity  
 2418 between video 9 and V1 in that respect – the locusts in video 9 also spend much time either  
 2419 on top of others, or in places where they are harder to see.

2420 Very short segments of mistaken identities (with a maximum length of less than 200ms)  
 2421 occurred whenever individuals "appear" only for a short moment and the segment does  
 2422 not contain enough data to be properly matched with a learned identity. Correct identities  
 2423 were reassigned in all cases after the individuals could be visually separated from each other  
 2424 again, and such events only make up  $< 1\%$  of the tracked data.

2425 Furthermore, we found that our method for posture estimation works well despite the  
 2426 more deformable bodies and complex 3D-postures of mice. Head and tail may switch occa-  
 2427 sionally, especially when animals shrink to "a circle" from the viewpoint of the camera. Over-  
 2428 all, however, by far most samples are normalised correctly – as can be seen in *Appendix 12*  
*Figure A2* and *Appendix 12 Figure A3*.

| video                                    | # ind. | reviewed (%) | interpolated (%) | TRex            |
|------------------------------------------|--------|--------------|------------------|-----------------|
| (V1) <i>Romero-Ferrero et al. (2019)</i> | 4      | 100.0        | 6.41             | $99.6 \pm 0.0$  |
| (V2) D. Mink, M. Groettrup               | 4      | 100.0        | 1.74             | $99.82 \pm 0.0$ |

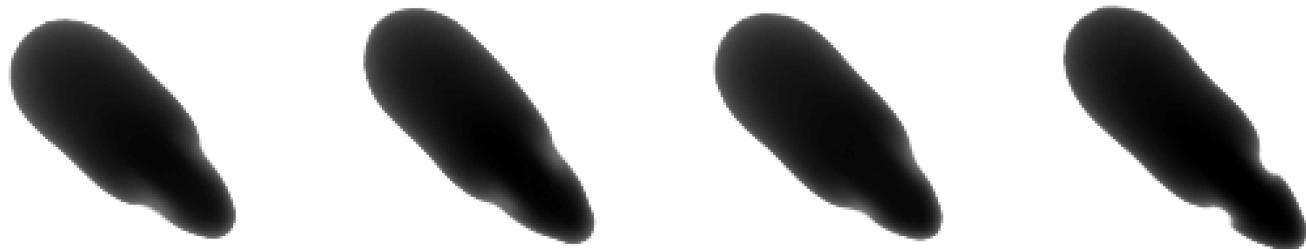
**Appendix 12 Table A1.** Analogous to our analysis in *Table 3*, we compared automatically generated trajectories for two videos with manually verified ones. Unlike the table in the main text, the sample size per video is only one here, which is why the standard deviation is zero in both cases. Results show very high accuracy for both videos, but relatively high numbers of interpolated frames compared to *Table 3*, where only the results for video 9 showed more than 8% interpolation and all others remained below 1%.



**Appendix 12 Figure A1.** Screenshots from videos V1 and V2 listed in [Appendix 12 Table A1](#). Left (V1), video of four "black mice" (17min, 1272x909px resolution) from [Romero-Ferrero et al. \(2019\)](#). Right (V2), four C57BL/6 mice (1:08min, 1280x960px resolution) by M. Groettrup, D. Mink.

**Appendix 12 Figure A1-video 1.** A clip of the tracking results from V1, played back at normal speed. Although it succumbs to noise in some frames (e.g. around 13 seconds), posture estimation remains remarkably robust to it throughout the video – sometimes even through periods where individuals overlap (e.g. at 27 seconds). Identity assignments are near perfect here, confirming our results in [Appendix 12 Table A1](#). <https://youtu.be/UnqRNKrYiR4>

**Appendix 12 Figure A1-video 2.** Tracking results from V2, played back at two times normal speed. Since resolution per animal in V2 is lower than V1, and contrast is lower, posture estimation in V2 is also slightly worse than in V1. Importantly, however, identity assignment is very stable and accurate. <https://youtu.be/OTP4dVSc7Es>



**Appendix 12 Figure A2.** Median of all normalised images (N=7161, 7040, 7153, 7076) for each of the four individuals from V1 in [Appendix 12 Table A1](#). Posture information was used to normalise each image sample, which was stable enough — also for TRex — to tell where the head is, and even to make out the ears on each side (brighter spots).



**Appendix 12 Figure A3.** Median of all normalised images (N=1593, 1586, 1620, 1538) for each of the four individuals from V2 in [Appendix 12 Table A1](#). Resolution per animal is lower than in V1, but ears are still clearly visible.