Mandipropamid as a chemical inducer of proximity for in vivo applications

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Direct control of protein interactions by chemically induced protein proximity holds great potential for both cell and synthetic biology as well as therapeutic applications. Low toxicity, orthogonality and excellent cell permeability are important criteria for chemical inducers of proximity (CIPs), in particular for in vivo applications. Here, we present the use of the agrochemical mandipropamid (Mandi) as a highly efficient CIP in cell culture systems and living organisms. Mandi specifically induces complex formation between a sixfold mutant of the plant hormone receptor pyrabactin resistance 1 (PYR1) and abscisic acid insensitive (ABI). It is orthogonal to other plant hormone-based CIPs and rapamycin-based CIP systems. We demonstrate the applicability of the Mandi system for rapid and efficient protein translocation in mammalian cells and zebrafish embryos, protein network shuttling and manipulation of endogenous proteins.

Protein proximity is a key regulatory mechanism in cellular processes, including metabolic pathways and cellular signaling, which are essential to sustain cellular integrity and to organize cellular response. Tools used to investigate and manipulate protein proximity have to meet a range of demanding requirements, such as fast dose–response, high efficiency and spatial control. At the same time, they should not interfere with the process under study or other cellular processes and they should not be cytotoxic. CIPs are small, drug-like molecules that induce protein proximity by mediating interactions between specific receptor and receiver domains (Fig. 1a) and have been widely used in biology. Different CIP systems have been successfully used to control protein proximity in various applications, such as signal transduction1–4, protein translocation5, degradation6 and aggregation7. Thus, they hold great potential for future drug development by specific control of metabolic pathways and signaling cascades8. The immuno-nosuppressant rapamycin (Si) is currently the best-studied CIP and has become well established to precisely manipulate cellular protein interactions9,6. However, while rapamycin was shown to be cell permeable and applicable in vivo, unwanted interaction with its endogenous target mammalian target of rapamycin (mTOR) can complicate the application of rapamycin as a CIP. Rapamycin analogs, so-called rapalogs, have been shown to be less toxic10,11, but their complex chemical structure can make them difficult to access. Therefore, there is high interest in novel CIPs that are orthogonal, that are chemically easily accessible and that exhibit excellent cell and tissue penetration behavior.

Phytohormone-based CIP systems have received significant attention over the past years because they make use of plant proteins, which do not occur in the animal kingdom and are therefore fully orthogonal to processes in mammalian cells. Gibberellic acid (GA; 6) as well as abscisic acid (ABA; 3) induce protein–protein interactions following ligand binding to regulate plant growth11 or stress resistance12 in plants. Both, GA and ABA in combination with their dimerization domains gibberellin-insensitive dwarf protein 1/gibberellic acid insensitive (GID1/GAI) and pyrabactin resistance-like (PYL)/ABI, respectively, have been used as CIP systems with times to effect in the range of minutes13,14. Recently, engineered ABA receptors have been reported for agrochemical control of water use in plants15. The genetically modified receptors do not respond to the phytohormone ABA but to the agrochemical Mandi (1), a fungicide extensively used in agriculture (Fig. 1b). A hextuple mutant PYRMandi of the ABA receptor PYR1 was identified that specifically binds Mandi15, replacing the natural ABA response in plants (Extended Data Fig. 1). On the basis of this finding, we decided to evaluate the PYRMandi mutant of the ABA receptor with Mandi as a CIP in mammalian systems, analogous to the use of the ABA system in previous works. The simple chemical structure of Mandi enables cheap and easy access to the molecule, and its low polarity also suggests very good cell and tissue penetration properties, which is of particular importance for in vivo applications. We demonstrate that the combination of the dimerization domains PYRMandi and ABI with Mandi as a CIP is a highly efficient CIP system to induce protein proximity in cellular systems as well as in vivo in an unrivaled fast and acute manner. Further, we show how the Mandi system can be used in conjunction with nanobodies to manipulate endogenous proteins. Finally, we demonstrate that the combination of the ABA and Mandi CIP systems allow for controlled and efficient shuttling of proteins between different cellular locations.
Fig. 1] Mandi, a new CIP. a, Chemically induced protein proximity to control interactions between proteins of interest A and B. b, Chemical structure of Mandi. c, Live-cell confocal microscopy of COS-7 cells cotransfected with pLYN-mCherry-PYR<sup>Staev</sup> and enhanced green fluorescent protein peGFP-ABI before and 2 min after Mandi addition (100 nM); data are representative of seven cells. d, Live-cell confocal microscopy of COS-7 cells transfected with pVim-mNeonGreen-PYR<sup>Staev</sup>-IRES-Halo-ABI and labeled with HaloTag ligand-SiR (HTL-SiR). Images were acquired before and 5 min after Mandi addition (50 nM); data are representative of 20 cells. The scale bars in c and d represent 10 μm. See Extended Data Fig. 2 for single-channel images.

Results

Characterization of Mandi as a new CIP. We hypothesized that, like the GA<sub>3</sub> and ABA systems, Mandi and the respective receptor PYR<sup>Staev</sup> can be used as a CIP in mammalian cells. With its simple molecular structure, Mandi is readily available either by chemical synthesis or commercially (Supplementary Table 1) as a pure compound. We therefore propose Mandi as an attractive candidate to overcome current limitations of CIP systems to leverage these tools for in vivo applications.

To test if Mandi can induce protein proximity in mammalian cells, we used a colocalization assay based on fluorescently labeled fusion proteins. We expressed the receptor domain PYR<sup>Staev</sup> fused to different intracellular proteins with characteristic localization and the receiver domain ABI as a cytosolic protein. Addition of Mandi resulted in rapid colocalization at the designated targets in all tested cell lines (Fig. 1c,d and Extended Data Fig. 2). While addition of Mandi to a final concentration of 1 μM resulted in efficient colocalization within seconds, colocalization using 100 nM Mandi was complete within 1 min. At 10 nM, colocalization was still detectable after 4 min, although less efficient (Supplementary Fig. 1 and Supplementary Videos 1 and 2). To quantitatively show the superior performance of a Mandi-based CIP system over existing approaches, we performed a direct comparison with other phytohormone-based CIP systems as well as the most commonly used CIP rapamycin (Fig. 2a). We used the acetoxyethyl (AM) ester-modified derivative of GA<sub>3</sub> (GA<sub>3</sub>-AM; 2) with improved membrane permeability<sup>13</sup>. For ABA we evaluated both, the commonly used unmodified carboxylic acid<sup>14</sup> and the so far not-reported corresponding AM ester (ABA-AM; 4). To determine the time to effect for each CIP, we extracted the recruitment kinetics for a cytosolic receiver to its corresponding receptor domain targeted to the outer mitochondrial membrane using a TOM20 fusion protein. Using an automated epifluorescence microscopy platform with integrated liquid handling, we performed time-lapse imaging after CIP addition and used a machine learning approach for automated cell segmentation and subsequent intensity readout<sup>15,16</sup> (Supplementary Figs. 2 and 3). This allowed us to measure times to effect for different CIP systems across a large number of cells for a quantitative comparison. Addition of ABA, ABA-AM and GA<sub>3</sub>-AM at a 5 μM concentration resulted in receiver recruitment to mitochondria measured as the translocation ratio <i>t</i><sub>50</sub> (the time at which translocation to mitochondria reached 75% of maximum; see Methods) values within 10 ± 0.8, 3.5 ± 0.1 and 2.4 ± 0.5 min (mean ± s.d.), respectively (Fig. 2b,c). By contrast, translocation induced by Mandi or rapamycin at the same concentration occurred too fast to be resolved in this assay. Therefore, we compared the translocation kinetics of Mandi and rapamycin at 500 nM CIP concentration (Fig. 2d and Supplementary Fig. 6) and observed a tenfold faster recruitment for Mandi (<i>t</i><sub>50</sub> of 10.1 ± 1.7 s) than rapamycin (<i>t</i><sub>50</sub> of 107.9 ± 16.4 s). Remarkably, at a 50 nM concentration, translocation induced by Mandi was still >1.2 times faster than with rapamycin at 500 nM (Fig. 2d). Although previous works successfully used ABA as a CIP without AM modification, our results also showed that a significant rate enhancement, presumably due to improved cell permeability, can be achieved for the ABA CIP system using the AM ester ABA-AM.

Previous studies showed that the high-affinity rapamycin system essentially functions as an ‘on/off switch’, whereas abscisic acid shows a dose–response profile with a large linear range, allowing concentration-dependent control of induced protein proximity<sup>17,18</sup>. To evaluate the dose–response dependency of Mandi-induced proximity, we used a gene expression assay with luciferase readout. Induced proximity between the yeast Gal4 DNA-binding domain (Gal4BD), preassociated with the Gal4 upstream activation sequence (Gal4UAS) and the viral VP16 transactivation domain (VP16), induces transcription of luciferase (Extended Data Fig. 3a). Similar to abscisic acid, a dose-dependent response of luciferase expression strength was observed for Mandi (Fig. 2e), which is advantageous for precise control of protein proximity. The comparison of the half-maximal effective concentration (EC<sub>50</sub>) showed an approximately 72-fold lower EC<sub>50</sub> value for Mandi (0.43 ± 0.17 μM; mean ± s.d.) than ABA (30.8 ± 15.5 μM; 95% confidence interval (95% CI)) and highlights the increased efficiency of Mandi. The tunability of Mandi-induced proximity could further be shown by dose-responsive activation of luciferase in a split tobacco etch virus (TEV) protease assay<sup>19</sup> (Extended Data Fig. 4).

To further characterize the interaction efficiency between receiver and receptor domains in the new Mandi CIP system, we measured the relative amount of receiver bound to receptor in the...
absence and presence of CIPs using raster image correlation spectroscopy (RICS)\textsuperscript{20}. After transient expression of cytosolic receiver and receptor domains fused to spectrally different fluorescent proteins, we determined the interacting fraction by computing the cross-correlation functions (CCF) between spectral channels and normalizing the obtained CCF amplitudes to controls with or without constitutive interaction between fluorophores\textsuperscript{21} (Extended Data Fig. 3b). Mandi and rapamycin showed similar interacting fractions of their respective receptor and receiver domains after stimulation with 500 nM CIP (Mandi, 77 ± 12%; rapamycin, 71 ± 3%; mean ± s.d.; Fig. 2f), whereas for ABA-AM, at the same concentration, only 41 ± 6% interaction was observed.

**Mandi-induced protein dimerization in vivo.** While CIP technologies for in vivo application are of broad interest, their translation from cellular systems to higher organism(s) is hampered
by demanding requirements for cell permeability, low toxicity and a favorable pharmacokinetic profile. Rapamycin is both toxic and immunosuppressive and, consequently, of limited use for applications in living organisms because of its narrow therapeutic window24. Rapalogs, which were developed to overcome these limitations, have been successfully used in vivo, for example, for caspase activation in mice25. However, due to their highly complex chemical structures, they are costly alternatives that forfeit some of the activity of rapamycin26. Heterobifunctional CIPs have been successfully applied in Xenopus embryos27, but the bifunctionality with different binding characteristics can lead to saturation of the binding sites at high concentration with formation of unproductive protein small-molecule conjugates, which has been described as the hook effect in the context of proteolysis-targeting chimeras (PROTACs)26,27. The use of GA3 and ABA as CIPs in a xenograft mouse model has been recently demonstrated but required intraperitoneal injection of the CIPs28, presumably because of limited cell permeability of both CIPs. As Mandi possesses drug-likeness with very low toxicity in mammals29 and shows fast and efficient induction of protein interactions, we hypothesized that it may be ideally suited for in vivo applications.

To test this, we expressed receiver and receptor domains on various cellular targets in zebrafish, Danio rerio, embryos and evaluated Mandi’s ability to induce protein proximity in tissue 3–5 d postfertilization (dpf; Fig. 3a). At concentrations as low as 500 nM, Mandi successfully induced protein colocalization within minutes at different subcellular targets, that is, in the plasma membrane or mitochondria and in different tissues (Fig. 3b–d, Extended Data Fig. 5 and Supplementary Video 3). Remarkably, addition of Mandi solution on top of the agarose-embedded embryos was sufficient to achieve colocalization in cells deep in the tissue (for example, muscle cells) within minutes, reflecting its excellent tissue penetration. As expected, based on risk assessments related to its use in agriculture30, signs of toxicity were not apparent under conditions in which zebrafish embryos were provided with 5 µM of Mandi for 72 h (Supplementary Fig. 7).

Nanobody-assisted targeting of endogenous proteins using CIP. Manipulation of endogenous proteins to enable protein interaction studies at native concentrations and in their physiological environment is highly desirable. However, tagging of endogenous proteins can result in altered expression patterns and ill-defined perturbations of protein function. Small drug-like probes for specific protein manipulation have been shown to be highly useful in cell biology research31; a generalization for use with arbitrary native proteins is, however, highly challenging. Recent advances using nanobodies have shown great potential for endogenous protein targeting in living cells30–33. We hypothesized that nanobody-assisted targeting in combination with the Mandi CIP system could induce artificial interactions between endogenous proteins and any genetically introduced effector protein in a dynamic and controlled manner. As a proof of principle in living cells, we used a well-studied anti-GFP nanobody34 in combination with cell lines stably expressing the F-actin-binding protein Lifeact–GFP or paxillin–yellow fluorescent protein (YFP). The anti-GFP nanobody and mCherry were expressed as fusion proteins with the Mandi receptor and receiver, respectively (Extended Data Fig. 6a). The nanobody thus serves as an adaptor between the native target and the artificial CIP system, placing the interaction of effector and endogenous target protein under strict control of Mandi. This was visualized by the appearance of characteristic structures following the addition of Mandi (Extended Data Fig. 6b,c and Supplementary Fig. 8). Provided that the nanobody does not interfere with the function of the endogenous protein of interest, this nanobody-assisted targeting of chemically induced protein proximity can be easily extended to other targets35.

Reversible multi-input CIP system with Mandi. The simultaneous use of multiple CIP systems allows for the construction of Boolean logic gates and enables the design of artificial genetic circuits13,36. For such applications, the CIP systems must be orthogonal to the organism under study and among themselves. We tested if the Mandi system could be used in conjunction with GA3- and

![Fig. 3 | Protein translocation in living zebrafish embryos.](image_url)
ABA-based CIP systems to create complex logic gates in cell culture systems. As expected, we found Mandi to be fully orthogonal to GA3 (Supplementary Fig. 9). ABA and Mandi, however, recruit the identical receiver domain ABI (Supplementary Fig. 10) and, therefore, can be used to create synthetic multi-input systems\(^7\), which are powerful tools for advanced applications previously only achievable using double fusion constructs\(^6\). To investigate potential cross-reactivity, we used three-color raster spectral image correlation spectroscopy (RSICS)\(^6\) to determine the interacting fractions at high CIP concentrations. While Mandi did not show any cross-reactivity with the PYL receptor domain, ABA(-AM) addition resulted in weak interactions between PYRMandi and ABI (Extended Data Fig. 7). Reducing the ABA-AM concentration to 200 nM minimized the undesired cross-reactivity to a negligible proportion (<10%).

A major challenge in synthetic biology is to mimic complex and highly dynamic intracellular protein networks and to further manipulate their regulation through external stimuli. We designed a multi-input protein translocation system based on different CIP systems where a cytosolic receiver protein is reversibly shuttled between different intracellular targets depending on the specific CIP input (Fig. 4a). Such applications are limited by competing interactions between multiple receptors and the receiver\(^7\). We addressed this problem by using the synthetic antagonist PANMe (7; Supplementary Fig. 11a)\(^6\), which we will call revABA hereafter, as a suppressor to selectively inhibit the interaction between ABI and PYL (Supplementary Fig. 11b,c and Supplementary Video 4). Consecutive addition of ABA-AM, revABA and Mandi allowed for controlled shuttling of the cytosolic receiver between mitochondria and vimentin filaments with high efficiency (Fig. 4b). Similar performance was also observed when changing the subcellular localization of receiver domains to the plasma membrane and mitochondria in HEK cells (Supplementary Fig. 12) or mitochondria and keratin filaments in COS-7 cells (Extended Data Fig. 8). We quantified the efficiency of recruitment of the receiver domain to the respective receptor domains by computing Pearson correlation coefficients between individual image pairs before or after small-molecule addition for shuttling between mitochondria and vimentin in COS-7 cells. This analysis confirmed that recruitment with each CIP and suppression of the ABI–PYL interaction with revABA was highly selective, and cross-activation of ABI–PYRMandi interactions were weak compared to specific induction of ABI–PYL interactions (Fig. 4c).

**Discussion**
In summary, we demonstrated that the Mandi CIP system is a versatile technology to control the localization and interaction of proteins and represents an attractive addition to the currently existing set of CIPs. The high cell permeability of Mandi enables immediate protein manipulation in living cells and organisms. We established the use of RICS to evaluate induced protein-binding efficiency in living cells and demonstrate the efficiency of Mandi in comparison to other CIP systems. In gene expression assays, we show that Mandi, comparably to ABA, possesses a large linear dose–response range and therefore has the potential to tune cellular processes in a concentration-dependent manner. Heterobifunctional CIPs have been successfully applied for that purpose, for example, in live cells to control kinetochore function\(^41\) and in vivo to control adhesion junctions within cell–cell contacts\(^7\). However, they can lead to hook effects\(^24\), whereas Mandi does not suffer from loss of activity at higher concentrations.

Mandi has an acute lethal dose to 50% of animals tested (LD\(_{50}\)) in rats of >5,000mg kg\(^{-1}\) and a no-observed adverse effect level (NOAEL) of 41mg kg\(^{-1}\)d\(^{-1}\) with no evidence of neurotoxicity or genotoxicity or carcinogenic potential in long-term studies\(^8\). Both, low toxicity and excellent cell permeability allow for Mandi to be used in complex organisms, as demonstrated by the rapid and

Fig. 4 | Reversible and dynamic protein shuttling in living cells. a. Schematic illustration of the four-step procedure to shuttle cytosolic protein between different intracellular targets. b. Confocal fluorescence microscopy images of the shuttling process between vimentin and mitochondria in a living cell. COS-7 cells were cotransfected with vimentin-mNeonGreen-PYR\(^\text{Mandi}\)–IRES–Halo-ABI and TOM20–SNAP–PYL. Halo-ABI and SNAP–PYL were labeled with HTL-SiR and tetramethylrhodamine (TMR)-Star, respectively. The top row shows dynamic receiver localization, and the middle row shows receptor localizations as references. Split images depict vimentin and mitochondrial localization in two different channels. The bottom row shows respective merged images. Images were acquired at the indicated times before and after the addition of ABA-AM (200 nM), after the addition of revABA (20 µM) and after the addition of Mandi (200 nM); scale bar 20 µm. Data are representative of 22 cells from two independent experiments. c. Pearson correlation coefficients (PCC; mean ± s.d.) between receiver and respective receptor channel images at the indicated time points for four-step shuttling between cytosol, mitochondria and vimentin as shown in b. Small symbols represent individual cells at the indicated time points. In the inset, conditions were compared with a two-sided paired t-test.
efficent protein translocation in living zebrafish embryos. In combination with specific nanobodies, we extend the applicability of Mandi to endogenous proteins of interest. By using the Mandi CIP system in conjunction with the ABA-AM system and the abscisic acid antagonist revABA, we realized highly controlled protein shuttling as a basis for advanced manipulation of protein interaction networks.

With respect to these findings, we expect Mandi-based technology to become a versatile and widely used tool for manipulating protein localization and interaction in cell biological research as well as for circuit design in synthetic biology. In consideration of the recent progress of humanized gene therapies and proximity-induced protein degradation, we speculate that the herein reported Mandi CIP system has the potential to be translated into therapeutic applications.42,43

Online content
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Methods

Plasmids. For the construction of plasmids, fragments were amplified by PCR from appropriate sources (see Supplementary Information). Primers used for PCR (Supplementary Table 3) were delivered by Integrated DNA Technologies (IDT). The PCR reaction mix backbone fragments was digested with DpnI (addition of 10 µl of CutSmart Buffer + 1 µl of DPN1 to 50 µl of PCR mix and incubation at 37 °C for 1 h). All PCR fragments were purified by preparative agarose gel electrophoresis and extracted with a QIAquick gel extraction kit (Qiagen). Ligation by Gibson assembly was performed in equimolar ratios of all fragments. Plasmid sequences were validated by Sanger sequencing (Seqlab) using either standard primers or preselected sequence primers. See Supplementary Information for fragment sources and specific procedures for all plasmids used in this study (Supplementary Fig. 13). All plasmids will be made available via Addgene after final publication.

Cell culture, transfection and sample preparation. Cells were grown at 37 °C and 5.0% CO2 in Dulbecco’s Modified Eagle Medium (DMEM; Sigma-Aldrich) supplemented with 2 mM L-glutamine, 1 mM sodium pyruvate and 10% (vol/vol) fetal bovine serum. Cells were routinely passed after 2–3 or up reaching 80% confluency. Before seeding cells, type number 1 eight-well LabTek chambered coverslips (Thermo Fisher Scientific) were cleaned with 0.1 M hydrofluoric acid to improve cell attachment. Twenty-four hours before imaging, cells seeded in LabTek chambers were transiently transfected using FuGene HD (Promega) or TransIT-T2 (Mirus) transfection reagents according to manufacturer’s guidelines. Cells transfected with HaloTag or SNAP-tag fusion constructs were labeled before imaging. Growth medium was exchanged with staining solution containing either 200 µM HTL-SiR or 200 nM TMR Star (New England Bioslabs) in DMEM and incubated between 2 min (HaloTag labeling) and up to 1 h (SNAP-tag labeling).

For mitochondria staining, cells were incubated with 200 nM MitoTracker Orange CMTMRos (Thermo Fisher Scientific) in DMEM for 1 h according to manufacturer’s guidelines. All measurements were performed in Leibovitz L15 medium (Sigma-Aldrich). All used CIPs were purified by preparative HPLC. Lyophilized products were dissolved in DMSO, and stocks were diluted in L15 medium. Final DMSO concentrations were kept below 2% for all experiments. 

Protein shuttling and colocalization analysis. Samples with HEK293T (DSMZ) or COS-7 cells (ATCC) were prepared according to general remarks. Imaging was initiated in 150 µl of L15 medium. CIPs were subsequently added as 2×, 3× or 4× stocks in 150 µl of L15 medium, respectively. The final DMSO concentration was kept below 2%. Images were acquired after the incubation times indicated in the respective figures.

For quantitative analysis of shuttling efficiency, confocal z stacks were acquired at each time point, and individual cells in each stack were segmented manually. Pearson correlation coefficients between receiver channel and both receptor channels were then computed using custom-written ImageJ scripts. Each image was background corrected by subtracting a copy of the respective image that was smoothed by convolution with a 20-pixel Gaussian. After background correction, Pearson R values were calculated using the ImageJ plugin Coloc2 for each z slice separately. The final Pearson R value for each cell was obtained by averaging R values from individual z slices.

Nonano-body-assisted targeting of chemically induced protein proximity. The stable cell lines HeLa (Lifeact–GFP-Halo; a gift from J. Pfeiler, University of Osnabrück, Germany) and RFP (paxillin–YFP; a gift from A. Cavalcanti-Adam, Max-Planck Institute for Medical Research, Heidelberg, Germany) were transfected with pnanobody–PYRtext and pmCherry-ABI constructs 24 h before imaging. Growth medium was exchanged, and imaging was performed in 200 µl of L15 medium. Mandi was added at a 2× final concentration in 200 µl of L15 medium to a final concentration of 50 nM.

Wide-field epifluorescence microscopy. Wide-field imaging was performed using an inverted epifluorescence microscope equipped with an Apo TIRF ×100/1.49 NA oil immersion objective (Nikon). An iXonME L-EFA multilaser engine (Toptica Photonics) containing four lasers emitting at 405, 488, 561 and 640 nm was used as the light source and fiber coupled into the microscope using a TIRF illumination module (Nikon). Focus stabilization in time-lapse imaging was achieved using a perfect focus system (PFS3, Nikon). Excitation and emission light were separated using a quad-edge dichroic beamsplitter, and emitted light was additionally filtered using 605/670-nm (mCherry) and 525/550-nm (eGFP) bandpass filters, respectively. For 488-nm and 561-nm detection channels, GaAsP detectors were used for detection. Detection of signal following 638-nm excitation was performed using a photomultiplier tube as a detector. A pixel size of 110 nm and a scan speed of 2.4 µs per pixel with 2× line averaging were applied for all data acquisitions. The pinhole was set to a size of 1.2 Airy units. Z stacks were recorded with a spacing of 500 nm. Nikon Elements was used to control image acquisition and all connected devices.

Screening of CIP efficiency. Sample preparation. COS-7 cells were seeded into eight-well LabTek chambered coverslips. Transient transfection with plasmids expressing both receiver and reporter domains as cytosolic eGFP (cloning into pUCA11mTOM20-mCherry fusions linked with an IRES sequence was conducted as described above (Supplementary Table 3). The mCherry-tagged mitochondrial receiver or receptor served as signal for segmentation of mitochondria and to determine the area to which cytosolic eGFP-tagged protein was recruited (see below). Twenty-four hours after transfection, cells were washed once with 1.5 µl L15 medium and then imaged in L15 at room temperature. CIP solutions were freshly prepared from DMSO stocks at 2× final concentration in L15 before imaging.

Acquisition. Automated time-lapse epifluorescence imaging was performed on a Nikon epifluorescence setup described above. Multispectral images were acquired with alternating laser excitation between frames, where 488-nm excitation was controlled by an Arduino microcontroller synchronized to the eCCD camera. Typically, images were acquired with 50-ms exposure per image and variable lag times between individual image pairs depending on the typical times to effect for the individual CIP systems (Supplementary Table 2). The end point of the time-lapse was chosen so that no further recruitment of the cytosolic signal to mitochondria was observed. The total number of images per post-CIP addition time-lapse was kept constant to minimize differences due to photo bleaching or phototoxicity between CIPs. eGFP and mCherry were excited with CW laser illumination at 0.53- and 0.51-mW output at the objective corresponding to an average irradiance of 5.3 µW/cm² across the readout region. Emitted fluorescence was split using an Optosplit II image splitter (Cairn Research) equipped with a 560-nm longpass beam splitter (AHF Analysetechnik) and additionally filtered with 605/670-nm (mCherry) and 525/550-nm (eGFP) bandpass filters inserted in the reflected and transmitted light paths, respectively. Signals from both paths were recombined using a second 560-nm shortpass filter and two axis translation mirrors. Manual coarse alignment of both channels was achieved using 0.1-µm Tetraspek multifluorescent beads (Thermo Fisher Scientific) as reference. For each experiment, a single cell in each well was manually selected with receiver and receptor expression and general cell morphology as selection criteria. Automated data acquisition was then performed using a custom-written μManager® browser script. In brief, each acquisition consisted of a 488/561-nm excitation image pair before CIP addition (t₁), CIP addition, time-lapse acquisition and acquisition of a final t₁ + 1 µs image pair (Supplementary Fig. 2). Injection of CIP was performed with a computer-controlled Aladdin AD1000 microfluidic pump (World Precision Instruments) at a flow rate of 6 ml min⁻¹. CIP was added at equal volume and double final concentration followed by a 2- to 4-s delay to allow for mixing of medium in the well with the added CIP solution. This procedure was repeated for each well on one slide.

Data preprocessing. Acquired multidimensional image stacks were processed in Fiji® using custom-written analysis routines. Raw data were automatically checked for errors in illumination sequences, and corresponding image pairs were removed from time-lapse datasets. Across all acquisitions, <1% of image pairs were discarded during this step. Flat fielding to correct for differences in excitation intensity was performed by multiplying all images with a template image. Illumination profile templates were obtained by acquiring 20–30 images of surfaces homogeneously coated with Alexa Fluor 488 or TMR NHS esters for 488-nm and 561-nm excitation, respectively. Images were then averaged and normalized to the maximum value in the averaged image. To correct for variations in alignment of the microscope, new templates were measured for each round of experiments. Image pairs were spatially aligned with subpixel accuracy using the Image Stabilizer Plugin authored by K. Li (http://www.cs.cmu.edu/~kangli/code/landingPage.html). Tetrascalip beads (0.1 µm; Thermo Fisher Scientific) were used to transform correlation coefficients. Transformation coefficients were determined separately for each experiment.

Segmentation and intensity extraction. Raw image data were automatically segmented using the Trainable Weka Segmentation package⁵. Models for
classification of total cell area and mitochondria were trained by manual classification of ten randomly selected images from the entire dataset. The model for cell detection was trained and applied using 488-nm excitation images, which exhibit purely cytosolic signal. The mitochondria model was trained using 561-nm excitation images. The obtained segmentations were robust with respect to the average area occupied by mitochondria in any given image set, which typically was between 10 and 40% (Supplementary Fig. 3), and no systematic variation in segmented mitochondrial area in individual time-lapse datasets was observed (Supplementary Fig. 3b).

Regions of interest (ROIs) were obtained from Weka segmentation results by thresholding of segmentation maps. Cytosolic ROIs were obtained by computing the difference between the whole cell and mitochondria for each image pair. As expected, the whole-cell intensity in the 488-nm channel remained unchanged (<2% variation) after CIP addition, indicating that cell movement during time-lapse image acquisition was negligible (Supplementary Fig. 3c,d). After segmentation, average intensities for each ROI and image were extracted and included as text files. Acquisition timestamps were extracted from image metadata and included in text files.

Plotting. Translocation ratios were computed using intensities extracted from t/, t, image pairs and time-lapse data. All calculations and plots were created using MATLAB 2018a (The MathWorks). In the figures, all data were corrected for photobleaching using the decay in whole-frame intensity during acquisition. Then, the ratio of mean 488-nm intensity in the mitochondria and cytosol ROI for each frame of the time-lapse dataset was computed. The obtained ratios were corrected for the ratio before CIP addition (ratio, and the final ratio after time-lapse acquisition (ratio , ). No ratio was computed for frames with erroneous Illumination sequence. Datasets where segmentation was not reliable were identified using the average mitochondrial 561-nm signal over time and excluded from analysis. The fraction of cells excluded was <10% across all CIPs (Supplementary Table 2). All code required for acquisition and processing of raw data will be made available after final revision of the manuscript.

 Luciferase expression assay. Sample preparation. For luciferase expression experiments, cells were transfected during cell seeding. For each well, a mixture of 10 µl of OptiMEM and 0.3 µl of Lipofectamine 3000 was added to 10 µl of pGL 4.31 (Promega) and 200 ng of PM-CHF-FLuc (Promega) and pVP16AD-PYRMandi-IRES-GAL4BD-ABI/Luciferase expression assay. (Supplementary Fig. 3b). In the figures, all data were corrected for photobleaching below 25% for all species. Typical counts per molecule were ca. 2.05×106 for eGFP, 1×106 for mCherry, and 5.0×106 for YFP (488 nm) and 5.9×106 (561 nm) excitation powers, respectively. Laser powers were chosen to maximize the signal emitted by each fluorophore species and to maintain photobleaching below 25% for all species. Typical counts per molecule were ca. 25 kHz for eGFP, 15–20 kHz for YFP and 10 kHz for mCherry. To obtain reference emission spectra for each individual fluorophore species, four image stacks of 25 frames were acquired at the same imaging settings on single-species samples on each day. In addition, negative and positive cross-correlation control samples were measured on each day. All measurements were performed at room temperature.

Data analysis. RICS measurements were performed on a Zeiss LSM 880 system (Carl Zeiss) using a Plan Achromat x40/1.2 Korr DIC M27 water immersion objective. Objective. For measurement, 300–400 frames of 256×256 pixels were acquired with a 50-nm pixel size (that is, a scan area of 12.83×12.83 µm through the midplane of cells), a 0.25-µs pixel dwell time and 1.25 ms line and 314.57-ms frame time (corresponding to a 1.5–2 min of total acquisition time). Samples were excited with a 488-nm argon laser and a 561-nm diode laser at ca. 4.8-µW (488 nm) and 5.9-µW (561 nm) excitation powers, respectively. Laser powers were chosen to maximize the signal emitted by each fluorophore species and to maintain photobleaching below 25% for all species. Typical counts per molecule were ca. 25 kHz for eGFP, 15–20 kHz for YFP and 10 kHz for mCherry. To obtain reference emission spectra for each individual fluorophore species, four image stacks of 25 frames were acquired at the same imaging settings on single-species samples on each day. In addition, negative and positive cross-correlation control samples were measured on each day. All measurements were performed at room temperature.

Data analysis. RICS analysis followed the implementation described recently, which is based on applying the mathematical framework of fluorescence lifetime and fluorescence spectral correlation spectroscopy24 to RICS. Four-dimensional image stacks were imported in MATLAB (The MathWorks) from CZI image files using the Bioformats package41 and further analyzed using custom-written code. First, average reference emission spectra for each individual fluorophore species, four image stacks of 25 frames were acquired at the same imaging settings on single-species samples on each day. In addition, negative and positive cross-correlation control samples were measured on each day. All measurements were performed at room temperature.

Data analysis. RICS analysis was performed in the arbitrary region RICS (ARICS) framework22. To this aim, an ROI was selected in the time- and channel-averaged image frame containing a homogeneous region in the cytoplasm of cells. This approach allowed for the exclusion of visible intracellular organelles or pixels in the extracellular space. Image stacks were further processed with a high-pass filter (with a moving four-frame window) to remove slow signal variations and spatial inhomogeneities. Afterwards, RICS autocorrelation functions (ACFs) and pairwise CCFs were calculated for each image stack and fluorescence spectral correlation spectroscopy24 to RICS. Four-dimensional image stacks were imported in MATLAB (The MathWorks) from CZI image files using the Bioformats package41 and further analyzed using custom-written code. First, average reference emission spectra for each individual fluorophore species, four image stacks of 25 frames were acquired at the same imaging settings on single-species samples on each day. In addition, negative and positive cross-correlation control samples were measured on each day. All measurements were performed at room temperature.
Articles

CCFs allowed for the discrimination between weak and no binding (that is, in the absence of interactions, the CCFs are dominated by noise, and the RICS fit does not converge to meaningful parameters, as previously described48). In the latter case, the rel.cc was set to zero. Binding efficiencies were calculated by subtracting the residual average rel.cc measured in each cross-correlation channel of the negative control (containing two or three mixed fluorescent protein (FP) species) from the measured cross-correlation. The result was then normalized using the average rel.cc obtained from the positive cross-correlation controls (containing eGFP–mCherry or eGFP–YFP heterodimers). The positive controls account for imperfect alignment of the optical observation volumes and non-fluorescent states of the fluorescent protein tags (for example, due to limited maturation or dark states49,50). To ensure statistical robustness of the three-color RICS analysis and sufficient signal-to-noise ratios, the analysis was restricted to cells expressing all three fluorophore species in comparable amounts, that is, relative average signal intensities of less than three for all species.

Zebrafish strains. The AB,0, wild-type line (European Zebrafish Resource Centre EZRC, Karlsruhe) was used for all experiments. Zebrafish husbandry51 and experimental procedures were performed in accordance with German animal protection regulations (Regierungspräsidium Karlsruhe, Germany, 35-9185.64/BH KIT).

Real-time imaging of zebrafish embryos. peGFP–ABI and pTOM20-mCherry–PYRz/zz or pLYN-mCherry–PYRz/zz plasmids were injected into the yolk of one- to two-cell embryos52. Positive coexpressing 3- to 5-d-old embryos, which were immobilized on a microscopy slide using 0.5% low melting point agarose supplemented with 0.02% MESAB, were used. Embryos were imaged with a x63/0.9–NA HCX Apo water-dipping objective installed on a Leica TCS SP2 confocal microscope and the corresponding Leica LCS software (Leica). All experiments were performed at room temperature. Mandi in water (50 µM stock solution in DMSO; 500 nM final concentration) was added on top of the embedded embryos.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The datasets generated during this study are available from the corresponding author upon request. Plasmids will be deposited at Addgene. Source data are provided with this paper.

Code availability

MATLAB code for RSICS analysis is available at GitHub (https://github.com/ VaDu8989/SpectralFFS). Custom ImageJ/Fiji scripts for processing time-lapse microscopy data for analysis of CIP kinetics is available at GitHub (https://github.com/KlausYserentant/CIPKinetics).

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Author contributions

M.J.Z., K.Y. and R.W. designed this study. A.J.G. and M.J.Z. designed and cloned vectors. C.K. and J.B. synthesized revABA. M.J.Z. synthesized Mandi and ABA-AM and performed luciferase assays. K.Y. designed and established software for automated RSICS experiments. V.M. performed in vivo studies. M.J.Z., K.Y. and R.W. analyzed data. K.Y. analyzed microscopy data. V.D., A.P. and S.C. planned, performed and analyzed RICS experiments. V.M. performed in vivo studies. M.J.Z., K.Y. and R.W. analyzed data. K.Y. and D.-P.H. designed and established software for automated microscopy and data analysis. K.Y., K.P. and M.J.Z. performed live-cell microscopy. K.Y. analyzed microscopy data. V.D., A.P. and S.C. planned, performed and analyzed RSICS experiments. V.M. performed in vivo studies. M.J.Z., K.Y. and R.W. analyzed data. K.Y., D.-P.H., U.S., S.C. and R.W. supervised the research. M.J.Z., K.Y. and R.W. wrote the manuscript with support from all authors.

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Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Fig. 1 | Crystal structures of CIP-bound receptor-receiver complexes for abscisic acid and mandipropamid. a, PYR1-ABA-HAB1 complex bound by ABA. b, Molecular structure of (+)-abscisic acid. c, PYR1(K59R/V81I/F108A/F159L)-HAB1 complex bound by mandipropamid. No crystal structure for hextuple mutant PYR(Mandi) is available to date. d, Molecular structure of mandipropamid (Mandi). Crystal structures obtained from pdb entries 3JRQ and 4WVO and based on previous reports in the literature.
Extended Data Fig. 2 | Mandi-induced protein translocation to different subcellular targets. Live-cell fluorescence microscopy of COS-7 cells transiently transfected with receiver domains targeted to subcellular targets and cytosolic receiver domain. Images were acquired by epi- (a) or confocal (b-d) fluorescence microscopy before and 2 min (c) or 5 min (a,b,d) after addition of Mandi at indicated final concentrations. Transfection with pTOM20-mCherry-PYR<sup>stand</sup>-IRES-EGFP-ABI (a), pKeratin-mNeonGreen-PYR<sup>stand</sup>-IRES-Halo-ABI (b), pLYN-mCherry-PYR<sup>stand</sup> and peGFP-ABI (c), Vimentin-mNeonGreen-PYR<sup>stand</sup>-IRES-Halo-ABI (d). Halo-ABI was labeled with HTL-SiR. Scale bars 20 µm. Representative data for 6–20 cells in 1–2 independent experiments.
Extended Data Fig. 3 | Quantitative characterization of Mandi via control of transcriptional activation and RICS. a, Schematic illustration of CIP-induced luciferase expression related to Fig. 2e. b, Representative cross-correlation functions of YFP and mCherry signal in COS-7 cells transiently transfected with indicated constructs. Left: negative (YFP + mCherry) and positive (YFP-mCherry fusion) controls. Right: mCherry-ABI vs. YFP-PYR\textsuperscript{Mandi} before (top) and after (bottom) addition of 500 nM Mandi. Binding efficiency for shown mCherry-ABI vs. YFP-PYR\textsuperscript{Mandi} after Mandi addition cross-correlation: 73%.
Extended Data Fig. 4 | Chemically induced reconstitution of split proteases. a, Schematic illustration of CIP induced reconstitution of TEV protease followed by proteolytic activation of cyclic Luciferase. b, Normalized enhancement of cLuc activity induced by proteolytic activation at different Mandi concentrations. Box extends from 25th to 75th percentiles, whiskers from min to max, bar represents median. Conditions were compared using two-sided unpaired t-test with Welch’s correction. Representative data from one experiment of two independent experiments.
Extended Data Fig. 5 | Confocal fluorescence microscopy images of protein colocalization on different cell types in living zebrafish embryos. Cytosolic receiver and mitochondria localized receptor domains expressed in zebrafish embryos. a, epithelial cell b, muscle cell. Images acquired before and 10–20 min after addition of Mandi. Scale bar 40 µm. Data representative for 3 independent experiments.
Extended Data Fig. 6 | Nanobody assisted targeting of chemically induced protein proximity. **a**, Schematic illustration (a) of nanobody assisted targeting of chemically induced protein proximity. **b**, HeLa cells stably expressing LifeAct-GFP were transfected with anti-GFP-nanobody-PYR\textsuperscript{Mandi} and mCherry-ABI fusions. Confocal images acquired before and 5 min after addition of Mandi. Pearson’s correlation coefficients indicated in images. Representative data for 30 cells in 2 independent experiments. Scale bar: 20 µm. **c**, Line profiles of GFP and mCherry signal intensity in ROI (yellow box) before and after addition of Mandi.
Extended Data Fig. 7 | See next page for caption.
Extended Data Fig. 7 | RSICS measurements of Mandi CIP system. a, Schematic of RSICS in the ARICS framework. A 256x256 pixel image stack of 300–400 frames acquired in 23 spectral channels is decomposed into three three-dimensional image stacks for GFP (G), YFP (Y) and mCherry (Ch), using a spectral filtering algorithm. An arbitrary ROI delimiting a homogeneous region in the cytoplasm is selected and RSICS analysis is applied to each frame of each image stack. b, c CCFs in the three cross-correlation channels obtained from three-color RSICS measurement on COS-7 cells co-expressing EGFP-PYL, YFP-PYR<sup>Mandi</sup> and mCherry-ABI performed 15 min after incubation with 5 µM ABA-AM (b) or 5 µM Mandi (c). d, Binding efficiencies for the Mandi/ABA CIP systems in the presence of 5 µM ABA-AM or 5 µM Mandi. For comparison, the binding efficiencies obtained in the negative (neg.) and positive (pos.) cross-correlation control samples are shown. Small symbols: individual data points corresponding to RSICS measurement in a single cell. Large symbols: means from experiments. Mean±SD across experiments indicated by horizontal lines. Data pooled from two independent experiments with 13 (neg.), 18 (ABA-AM), 19 (Mandi) and 16 (pos.) cells. e, Binding efficiency of PYR<sup>Mandi</sup> vs. mCherry-ABI in the presence of 200 nM ABA-AM measured by two-color RSICS. For comparison, the binding efficiencies obtained in the negative (neg.) and positive (pos.) cross-correlation control samples measured under identical conditions are shown. Mean±SD across experiments indicated by horizontal lines. Data pooled from 2 (neg, pos) or 3 (ABA-AM) independent experiments with 28 (AB-AM), 10 (neg) and 20 (pos) cells.
Extended Data Fig. 8 | Reversible and dynamic protein shuttling between mitochondria and keratin in living cells. COS-7 cells were co-transfected with Keratin-mNeonGreen-PYR(\textsuperscript{Mandi}).IRES-Halo-ABI and TOM20-SNAP\textsubscript{P}-PYL. Halo- and SNAP-tag domains were stained with HTL-SiR and TMR-Star 2 h prior to imaging. a, Representative confocal fluorescence microscopy images of four-step shuttling between cytosol, mitochondria and keratin over time. Upper row shows dynamic receiver localization, middle row receptor localizations as references, lower row respective merges. Images acquired at t\textsubscript{0}, 10 min after addition of ABA-AM (200 nM), 25 min after addition of revABA (20 μM), 10 min after addition of Mandi (200 nM). Scale bar 20 μm. b, Pearson correlation coefficients (PCC) between images receiver and respective receptor channel images at indicated time points for four-step shuttling between cytosol, mitochondria and keratin as shown in (a). 4 cells from 1 experiment. Mean±SD across all cells indicated by dark circles and error bars.
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- The statistical test(s) used AND whether they are one- or two-sided
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- A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
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*Our web collection on statistics for biologists contains articles on many of the points above.*

Software and code

Policy information about availability of computer code

**Data collection**
- Confocal microscopy: NIS-Elements AR Version 5.11.01 (Nikon)
- Epifluorescence microscopy: MicroManager Version 1.4.23. Described in Edelstein et al., J Biol Methods (2014).
- RSICS: Zen Version 2.1 (Zeiss)
- In vivo confocal microscopy: TCSNTV (Leica)
  - Plate reader: Tecan Spark (Tecan)

**Data analysis**
- Fluorescence microscopy data: Image/Fiji Version 1.52p. Described in Schindelin et al., Nat. Methods (2012).
- Plotting and in-cell CIP kinetics: Custom Matlab code, MATLAB Release 2018a (MathWorks) as described in Methods.
- Mass spectrometry: ESI-Compass 1.3 Version 4.0 (Bruker).
- NMR: MestReNova Version 9.0.1 (Mestrelab Research).
- Unsupervised segmentation of fluorescence microscopy images: Trainable Weka Segmentation. ImageJ plugin, version 3.2.33. Described in Arganda-Carreras et al. Bioinformatics (2017).
- Alignment of multispectral fluorescence microscopy images: Image stabilizer developed by Kang Li. Obtained via http://www.cs.cmu.edu/~kang/code/Image_Stabilizer.html
- RSICS: Custom Matlab code, MATLAB Release 2015b as described in Methods, following published literature.
- Gene Expression: Custom Matlab code, MATLAB Release 2015b
- Split Prototype: GraphPad Prism 9.1.2

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. Github). See the Nature Research guidelines for submitting code & software for further information.
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Life sciences study design
All studies must disclose on these points even when the disclosure is negative.

| Sample size | No statistical methods were used to predetermine sample sizes. The number of cells/embryos assayed per condition and experiment was chosen such as to minimize the time samples (cells, embryos) were kept on the microscope. For all samples at least 2 repetitions were performed. |
| Data exclusions | In general, cells/embryos were selected for imaging based on the expression strength of transfected constructs. Cells/embryos with weak or strong expression not representative for population of transfected cells were not used for experiments. |
| - in cell CIP kinetics: Cells where segmentation was not reliable were identified using the average mitochondrial 561 nm signal over time and excluded from analysis. The percentage of discarded cells per condition is stated in supplementary table 2. |
| - RSICS experiments: Measurements with average expression levels differing by more than a factor of 3 between the three fluorophore species were excluded as stated in the Methods section. |
| - Protein shuttling: No cells were excluded from analysis. |
| Replication | All experimental findings were reproducible in at least two independent experiments. The specific number of experiments and replicates for each experiment is stated in the corresponding figure caption. |
| Randomization | n/a - no allocation into experimental groups was performed. |
| Blinding | n/a - no allocation into experimental groups was performed. All quantifications are based on automated analysis workflows without user interference. |

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| □ | |
| Human research participants | |
| □ | |
| Clinical data | |
| □ | |
| Dual use research of concern | |
| □ | |
Eukaryotic cell lines

Policy information about cell lines

- HEK293T and COS-7 cells were obtained from ATCC.
- REF cells expressing YFP-Paxillin were obtained from Ada Cavalcanti-Adam (Max-Planck Institute for Medical Research).
- HeLa cells expressing LifeAct-eGFP-HaloTag were obtained from Jacob Piehler (Universitaet Osnabrueck).

Authentication

- All Cell lines were used without authentication.

Mycoplasma contamination

- None of the cell lines used was tested for Mycoplasma contamination.

Commonly misidentified lines (See ICCLAC register)

- HEK293T cell lines were used due to their suitability in visualizing plasma membrane-localized reporters.

Animals and other organisms

Policy information about studies involving animals: ARRIVE guidelines recommended for reporting animal research

- **Laboratory animals**: Danio rerio, AB202 wildtype, larvae 3-5 days post fertilization
- **Wild animals**: n/a - no wild animals were used.
- **Field-collected samples**: n/a - no wild animals were used.
- **Ethics oversight**: Regierungspräsidium Karlsruhe, Germany, 35-9185.64/BH KIT

Note that full information on the approval of the study protocol must also be provided in the manuscript.